THE ROLE OF SENSORY FEEDBACK ON THE COORDINATION DYNAMICS OF A LIMB AND A VOICE TASK

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Although it is generally acknowledged that sensory feedback is required to fine tune movement patterns, its role in coordinative dynamics has received less attention. Experiment 1 investigated the role of visual and auditory feedback on 0º and 180º relative phase patterns at increasing frequency of oscillation for a bimanual limb task. The dependent variables were mean error of relative phase and standard deviation of relative phase. Results indicated that the visual and auditory feedback conditions did not influence the accuracy and the variability in performance of the 2 relative phase patterns, whereas increasing frequency influenced the performance of the 180º relative phase pattern, but not the 0º relative phase pattern. Experiment 2 investigated the role of auditory feedback on breathy, normal, and pressed voice qualities at increasing fundamental frequency for a voice coordination task. The dependent variables were mean of laryngeal resistance (cmH2O/l/s) and standard deviation of laryngeal resistance (cmH2O/l/s). Results indicated that the masked auditory feedback condition significantly increased variability in performance across all 3 voice qualities and specifically, the masked auditory feedback condition facilitated significantly higher mean laryngeal resistance values for the pressed voice quality but not for the breathy and the normal voice qualities. As a potential explanation of the current findings in Experiment 1, it is hypothesized that the bimanual coordination task did not rely on visual and auditory feedback because the task was governed by proprioceptive feedback, which was not controlled in the present study. For Experiment 2, sensory feedback may be relevant for voice patterns that have a shallow basin of attraction (i.e., pressed voice), but irrelevant for voice patterns that have a steep basin of attraction (i.e., breathy and normal voice). Perhaps the breathy and normal voice qualities were governed by voice coordination dynamics, while the pressed voice quality was partly influenced by auditory feedback connections. In addition, level of expertise may also play a role in the coordination dynamics of a voice task. The influence of auditory feedback on voice coordination dynamics suggests an expanded view of dynamic systems theory and supports the role of auditory feedback in vocal rehabilitation.

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PREFACE

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1.0 CHAPTER 1: INTRODUCTION

Motor control and motor learning are core issues in many rehabilitation programs involving occupational, physical and speech therapy. Consequently, just as investigations into pharmaceutical agents and surgical tools are central to the practice of medicine and surgery, investigations into motor control and motor learning are central to rehabilitation science. Surprisingly, theoretical explorations of the mechanisms by which people acquire new physical skills and override old ones have largely been overlooked in the rehabilitation literature (see however, Buchanan & Ulrich, 2001; Gonnella, Hale, Ionta & Perry, 1981; Hochstenbach & Mulder, 1999; Latash & Anson, 1996; Mulder, 1991; Mulder, Zijlstra, Zijlstra, & Hochstenbach, 2004; Rouselle & Wolff, 1991; Scholz, 1990; Smethurst & Carson, 2001; Winstein,1991; Woolridge & McLaurin, 1976).

Complicating such investigation are theoretical debates that have raged across two primary contemporary accounts of motor control and motor learning: schema theory, which emphasizes a generally top-down approach with covert rules for movement constructed by the actor (Schmidt, 1975, 1976, 2003) and dynamic systems theory, which is generally bottom-up in emphasizing coordinative factors that exist independent of the actor (Haken, Kelso & Bunz, 1985; Jeka & Kelso, 1989; Kelso, 1995; Wallace, 1996). A central issue in the debates has regarded the relative contribution of a hypothetical "generalized motor program" (GMP) versus synergistic dynamics to motor control and learning. Schema theory asserts a central role of a GMP, conceived as a command function causal to movement, and executed by the biomechanical system. In contrast, dynamic systems theory takes the opposite approach, claiming that the motor system self-organizes according to synergistic principles of coordinated structures without any necessary command functions.

Somewhat in contrast to both approaches, recent neurophysiological research points to a dynamic *heterarchy* of nervous system organization and function in which influences are seen from top-down, bottom-up, and horizontal operations (Crick & Koch, 1990, 2003; Davis, 1976; Edelman, 1987; Guillery & Sherman, 2002; Jones, 2001; Mountcastle, 1979). To the extent that theories of motor control and learning seek coherence across behavioral and neurophysiological data, what is needed is an expanded theory of motor control and learning that is consistent with recent behavioral as well as neurophysiological views of nervous system organization and function. The present studies, which are conducted with a general dynamic systems framework, address this theoretical need as well as a practical one. The theoretical pursuit regards the relevance of heterarchical features in motor control and specifically, the role of sensory feedback (i.e., vision and audition) on the coordination dynamics of a limb and a voice task. The practical focus is a newly developing *Global Voice Therapy Program* that emphasizes the importance of auditory and kinesthetic feedback in voice training (Grillo, in preparation).

In sum, the present studies are motivated by a convergence of theoretical and practical concerns. This chapter provides critical background information addressing the following issues: (1) basic foundations of nonlinear dynamics, (2) dynamic systems theory applied to motor behavior and the Haken, Kelso, and Bunz (HKB) (1985) model including predictions and limitations, (3) gaps in the literature addressed in the present studies, (4) further extension of dynamic systems theory perspective to the case of voice production, and (5) statement of purpose, specific aims, experimental questions, and hypotheses in the present series.

1.1 BASIC FOUNDATIONS OF NONLINEAR DYNAMICS

1.1.1 Concepts related to the field of nonlinear dynamics

The next sections provide an overview of elemental concepts in nonlinear dynamics with specific reference to linear versus nonlinear systems and dynamic systems. Key concepts are also defined including order parameters, control parameters, and stability.

1.1.2 Linear versus Nonlinear Systems

In geometry, linearity refers to lines, planes, and flat three-dimensional space with predictable linear trajectories. Linear objects and resultant linear trajectories appear the same no matter how they are examined (Farin & Hansford, 2005). Conversely, nonlinear behavior is any behavior that suddenly deviates from a previously smooth and predictable linear trajectory (Slotine & Li, 1991). For example, a nonlinear object, such as a sphere, deviates from a predictable linear trajectory when it is viewed from different vantage points. A sphere looks like a sphere from 2 feet away; however, when the sphere is viewed from 50 feet away it looks like a point. These deviations or discontinuities from predictable linear behavior have been recognized in many scientific fields (e.g., physical, chemical, biological), but have not been seriously studied in behavioral research until recently (Briggs & Peat, 1989; Campbell, 1987; Gleick, 1987; Haken, 1983, 1984, 1988; Haken, Kelso & Bunz, 1985; Laskar, 1989; Lorenz, 1963; Slotine & Li, 1991). One reason for this lack of investigation is that nonlinear behavior has often been considered an anomaly and sometimes even noise within various systems. The smooth, predictable, linear aspects of behavior, therefore, have traditionally garnered most of the attention in science (Briggs & Peat, 1989).

In fact, from the time of Newton and his laws of motion; science has been preoccupied with describing the order in nature through predictable linear behaviors and equations (Fauvel, Flood, Shortland & Wilson, 1988). For example, in the following linear equation a change in the known independent variable (x) leads to a proportional change in the dependent variable (y) (Fauvel et al., 1988).

If $x=y$, then $4x=4y$, $16x=16y$, and so on for all values of x and y.

Of course, this type of linear equation has been helpful in many human enterprises, such as measuring the weight of objects, building bridges, and early theorizing about speech production. The traditional source-filter theory of speech production suggested a linear equation (Fant, 1960).

Vocal fold vibration + filter functions → speech output.

Recent research, however, suggests that the linear source-filter theory of speech production (Fant, 1960) is inadequate in describing speech production due to the nonlinear behavior between the filter function and vocal fold vibration (Austin & Titze, 1997; Titze & Story, 1997). Although the source-filter theory of speech production has been the predominant model of speech for nearly half a century, a perusal of the literature indicates that vocal fold vibrations in voice production were originally described by nonlinear equations as self-sustained oscillations (Ishizaka & Flanagan, 1972; Ishizaka & Isshiki, 1976).

1.1.3 Dynamic Systems

Nonlinear science is interrelated with the concept of dynamic systems. Dynamic systems are complex systems composed of two or more component parts that self-organize with a continuous flow of energy in and out of the system (Coveney & Highfield, 1990; Gleick, 1987;

Hale & Kocak, 1991; Kelso, Holt, Kugler & Turvey, 1980; Kugler, Kelso & Turvey, 1980; Prigogine & Stengers, 1984). According to the movement sciences literature, the component parts interact for production of functional gestures (Kelso et al., 1980; Kugler et al., 1980; Turvey, Rosenblum, Schmidt & Kugler, 1986). The component parts of a dynamic system are proposed to be self-organized, and thus the need for a central command structure is eliminated. Moreover, according to dynamic system theory of motor behavior, central commands would be unfavorable to movement production because they would slow down the movement system (Kelso et al., 1980; Kugler et al., 1980).

Dynamic systems are nonlinear and consist of a phase space (Coveney & Highfield, 1990; Gleick, 1987; Hale & Kocak, 1991). The phase space specifies the system completely by predicting how the system will function in the immediate future. The patterns of behavior that exist in the phase space can be finite (e.g., two states for the ideal coin toss, head or tails) or infinite (e.g., all real numbers as possible states) (Coveney & Highfield, 1990; Gleick, 1987; Hale & Kocak, 1991). The coordinates of the phase space describe the dynamic system at any instant and specify the immediate trend of all variables given the initial conditions of the dynamic system variables (Coveney & Highfield, 1990; Gleick, 1987; Hale & Kocak, 1991). Dynamic systems can be deterministic or random depending upon the number of reasonable outcomes from a defined probability distribution (Campbell, 1987; Gleick, 1987; Hale & Kocak, 1991). A deterministic dynamic system requires a unique reasonable outcome for every possible state, whereas a random dynamic system has more than one reasonable outcome for every possible state (Campbell, 1987; Gleick, 1987; Hale & Kocak, 1991). Most nonlinear dynamic investigations deal with deterministic systems.

1.1.4 Order and Control Parameters

Order parameters are indices along which patterns of behavior emerge from the internal self-organization of the component parts of a dynamic system (Haken, 1984, 1988). In contrast, *control parameters* are external variables that influence the patterns of behavior (Haken, 1984, 1988). Stated differently, the order parameter can be seen as a dependent variable, whereas the control parameter can be seen as an independent variable. The control parameter does not carry information about how it will influence the behaviors, but rather guides the dynamic system through the various behaviors on a moment-to-moment basis (Haken, 1984, 1988). To better illustrate the distinction between order and control parameters, consider heating oil in a pan for cooking vegetables. As the pan is gradually heated, the order parameter of the oil molecules achieves a pre-boiling state in which cooler oil molecules are positioned on the surface of the pan and warmer molecules are positioned on the bottom of the pan. As the temperature increases, the order parameter of the oil molecules reaches the boiling state as hot oil molecules consume the pan. The order parameter of the oil molecules (e.g., pre-boiling versus boiling) was influenced by changes in an external variable or control parameter (e.g., heat). Proponents of dynamic system theory in motor behavior propose that order parameters emerge from self-organization within the movement system, whereas control parameters represent all external variables that influence the movement system, including frequency of oscillation and environmental constraints (Fowler & Turvey, 1978; Kugler & Turvey, 1987; Newell, Kugler, van Emmerik & McDonald, 1989).

1.1.5 Stability

Another important principle in nonlinear dynamics is "stability" or resistance to change within a dynamic system (Kelso et al., 1980). In the preceding illustration around heated oil molecules, the pre-boiling state was stable for a short time before it was replaced by the boiling state when heat was added from the control parameter. Stated differently, each behavior pattern (e.g., pre-boiling and boiling) has stability or a resistance to change once the pattern is established. Stability of a behavior pattern, however, can be overcome by the influence of a control parameter as demonstrated in the oil molecules example. That is, the continuous scaling of a control parameter (e.g., heat) produces a discrete shift in the order parameter (e.g., oil molecule activity). The concept of stability and loss of stability lies at the heart of nonlinear dynamic systems theory and will be discussed later in the chapter.

To summarize, component parts of nonlinear dynamic systems are self-organized for production of functional gestures. Order parameters are the index along which patterns of behaviors emerge from the dynamic system. External variables called control parameters can act upon the dynamic system and push it into different patterns of behavior. These core concepts provide a framework within which to understand the most elemental theoretical constructs that govern dynamic systems theory's predictions around motor behavior.

1.1.6 Historical Review of the Field of Nonlinear Dynamics

The relevance of dynamic systems theory is perhaps best appreciated within the larger context of the history of science. Some historians would agree that the foundations of contemporary physical science had origins with Isaac Newton's *Principia* published in 1686

(Briggs & Peat, 1989; Coveney & Highfield, 1990; Fauvel et al., 1988). In *Principia*, Newton attempted to describe the state and motion of a body in space as well as factors that influence the body's motion (see Fauvel et al., 1988 for a biography of Newton's life and scientific contributions). Newton's laws, as described in *Principia*, present a linear, predictive description of factors that govern and influence the trajectory of a body in space (Fauvel et al., 1988). The linear explanation of bodies in space allowed for the study of isolated parts within a complex system, such as the planetary system. The notion was that if the isolated parts of a complex system could be understood, then a simple reassembly of them would result in an understanding of the whole. This *reductionist* approach, which broke the behavior of dynamic systems up into its component parts, became a pervasive paradigm throughout science (Briggs & Peat, 1989; Coveney & Highfield, 1990; Fauvel et al., 1988). The reductionist approach is still prevalent today as seen in efforts to search for the building blocks of life, map smaller and smaller areas of the brain, and identify central pattern generators in the central nervous system (CNS). The reductionist approach has made significant contributions to the understanding of nature; however, proponents of nonlinear dynamics believe that the emphasis on microscopic behaviors in isolation does not allow for a full description of dynamic, complex systems (Campbell, 1987; Gleick, 1987).

A threat to Newtonian mechanics and the reductionist approach began to emerge by the 19th century (Briggs & Peat, 1989; Coveney & Highfield, 1990; Gleick, 1987; Prigogine & Stengers, 1984). The threat arose from observations of macroscopic features of complex systems rather than individual or microscopic elements. Interestingly, this threat to Newtonian mechanics began with an innocent interest in the behavior of heat, but developed into a major domain of inquiry within physics called thermodynamics (Briggs & Peat, 1989; Coveney &

Highfield, 1990; Gleick, 1987; Prigogine & Stengers, 1984). Thermodynamics focused primarily on complex systems and the macroscopic features of those systems at or close to equilibrium (Briggs & Peat, 1989; Coveney & Highfield, 1990; Gleick, 1987; Prigogine & Stengers, 1984).

Two laws emerged from the study of thermodynamics. The first law states that total energy in a system cannot be created or destroyed and the second law states that in any conversion between heat and work some energy is lost (Briggs & Peat, 1989; Coveney & Highfield, 1990; Gleick, 1987; Prigogine & Stengers, 1984). In 1865, Clausius re-formulated the second law using a new concept he dubbed *entropy*, defined as the degree to which a complex system has the capacity for change (Briggs & Peat, 1989; Coveney & Highfield, 1990; Gleick, 1987; Prigogine & Stengers, 1984). A complex system that has a considerable capacity for change is said to have *low entropy*, whereas a complex system that has a minimal capacity for change is said to have *high entropy* (Briggs & Peat, 1989; Coveney & Highfield, 1990; Gleick, 1987; Prigogine & Stengers, 1984). In a high entropy condition, the system has reached a state of equilibrium in which no exchange of energy occurs, therefore, it is not likely that the system's behavior will change. Conversely, a complex system that has reached low entropy or a non-equilibrium condition is more likely to change (Briggs & Peat, 1989; Coveney & Highfield, 1990; Gleick, 1987; Prigogine & Stengers, 1984). Additionally, if a system is exposed to outside energy sources or control parameters, the system will be pushed to high or low entropy conditions depending upon the type and degree of the control parameter (Haken, 1984, 1988).

A complex system, however, is usually attracted to high entropy or equilibrium (Briggs & Peat, 1989; Coveney & Highfield, 1990; Gleick, 1987; Prigogine & Stengers, 1984). For example, a ball pushed down a hill will eventually end up at the bottom of the hill in a state of equilibrium or high entropy. High entropy, in the ball condition, is a strong attractor with a steep basin of attraction because once the ball reaches the bottom of the hill, the system cannot return to its initial conditions unless a control variable acts upon the ball or the hill. In fact, the condition of high entropy can be considered an "attractor state", as discussed later in the chapter as it pertains to movement systems within the human body.

An important figure in the development of dynamic systems theory of motor behavior was Herman Haken, a German physicist. Haken described how the emission of incoherent light from a laser device can suddenly switch to a coherent light wave as the control parameter of electric current is increased (Haken, 1977). As indicated previously, the control parameter is any external variable that can push the complex system into different behavior patterns and the order parameter is the description of the actual patterns that emerge (Haken, 1984, 1988). The order parameter reflects some type of relationship among the individual components of the complex system. Haken challenged scientists to define the control and order parameters within specific biological systems. Investigation of the order and control parameters within a biological system is the study of synergetics –an interdisciplinary approach to understanding self-organization in complex systems (Haken, 1983, 1984, 1988, 1991). Synergetics applied to movement coordination has been termed the dynamic pattern perspective or dynamic systems theory (Haken et al., 1985; Jeka & Kelso, 1989; Kelso, 1995; Schöner, 1990; Schöner & Kelso, 1988a). The synergistic strategy emphasizes the search for patterns among the component parts of a self-organized, complex system, as well as the description of how the patterns change.

The application of nonlinear dynamic systems to human movement may have initiated with two seminal chapters that introduced the theoretical constructs of synergetics to movement coordination (Kelso et al., 1980; Kugler et al., 1980). Essentially, this application of nonlinear dynamic systems and synergetics to human movement was formulated to solve Bernstein's (1967) *degrees of freedom* problem. Bernstein's degrees of freedom problem refers to the problem of how the body can control the many independent parts of a movement system without "too much" regulation from central command processes. Bernstein (1967) theorized that control of an action in a complex system was possible only because of functional synergies between the muscles and joints, thus limiting the need for central command functions. This is not to say that Bernstein did away with a central command function in its entirety. Rather, he emphasized functional synergies that release some of the burden from hypothetical central command functions. Dynamic systems theorists, however, essentially followed a line of thinking that the functional synergies proposed by Bernstein (1967) left the action system independent from a central control (Haken et al., 1985; Kelso et al., 1980; Kugler et al., 1980).

According to Turvey (1990), the degrees of freedom problem postulated by Bernstein prompted two rounds of theorizing. The first round of theorizing in the 1960s and 1970s attempted to identify coordinative components of dynamic, biological systems (Gelfand, Gurfinkel, Tsetlin, &Shik, 1971; Greene, 1972). Early research on identification of dynamic structures followed Bernstein's (1967) functional synergies approach. Functional synergies were discovered that underlie coordinative patterns such as locomotion (Shik & Orlovski, 1976), aiming at a target (Arutyunyan, Gurfinkel & Mirsky, 1969), and maintaining an upright posture during breathing (Gurfinkel, Kots, Paltsev & Feldman, 1971). The first principle of dynamic systems theory of motor behavior, therefore, involves the identification of coordinative structures within a nonlinear dynamic system (Easton, 1972; Turvey, 1977).

The second round of theorizing in the 1980s and 1990s focused on the self-organization within a dynamic, coordinative system responsible for rhythmic movement. In line with this second round of theorizing, Kelso (1981, 1984) explored the nonlinear dynamics of rhythmic movement with two bimanual experiments in humans. The first experiment was conducted around bimanual finger movements (Kelso, 1981) and the second was related to bimanual wrist movements (Kelso, 1984). Across the series, subjects were required to produce simultaneous and cyclical (oscillatory) movements with the left and right index fingers or the left and right wrists. Independent variables included relational patterning of the movements and frequency of oscillations.

Relative to movement patterning, subjects were required to start a trial in one of two movement patterns: the in-phase pattern or the anti-phase pattern. In the in-phase or 0º relative phase pattern, the fingers or the wrists moved toward each other and then away from each other continuously using the same homologous muscle groups contracting at the same time (Kelso, 1981, 1984). In the anti-phase or 180º relative phase pattern, the fingers or wrists moved together in a parallel fashion with the homologous muscle groups contracting in an alternating fashion (Kelso, 1981, 1984).

The second independent variable was frequency of oscillations. The target frequency was provided by the pacing of an auditory metronome. Subjects were required to keep pace with the metronome by performing oscillations in time with the beat in Hertz (Hz). At the beginning of the trial, the metronome started at 1Hz and beeped 15 times at that frequency before being increased at steady increments of .25 Hz until a final oscillatory frequency of 3Hz was reached. Each set of 15 beeps at a given frequency was called a plateau. From this experimental paradigm, Kelso (1981, 1984) was able to calculate two dependent variables: mean relative phase error and the standard deviation around the mean within each oscillatory frequency plateau.

The results of the experiment indicated that subjects who initially performed the in-phase or 0º pattern stayed in the pattern as the oscillatory frequency increased from 1 Hz to 3HZ. Subjects who initially performed the anti-phase or 180º pattern maintained the pattern for oscillatory frequencies ranging from 1Hz to 2.25 Hz, however, standard deviations were greater than standard deviations for the 0º pattern (Kelso, 1981). At oscillatory frequencies ranging from 1-2.25 Hz, Kelso (1981) identified the 0º pattern and the 180º pattern as conditions of attractor states because of their stability as evidenced by limited variability. As the oscillatory frequency or control parameter was increased beyond 2.25 Hz, the 180º pattern lost stability and performance switched to the 0º pattern (i.e., the more stable of the two).

The switch in performance from the 180º to 0º pattern beyond the frequency of 2.25 HZ is called a phase transition (Kelso, 1981, 1984). After the phase transition was made to the 0º pattern, subjects did not switch back to the 180º even when the oscillatory frequency was slowed. According to dynamic systems theory, the effect of resistance to change once the 0º relative phase pattern was achieved is consistent with a condition of high entropy or an attractor state. The 180º pattern was also classified as an attractor state for frequencies ranging from 1 Hz to 2.25 Hz.

Based on the results of Kelso's (1981, 1984) experiments, Haken, Kelso, and Bunz (1985) developed a theoretical model to describe the coordinated behavior exhibited in a simple two-finger and two-wrist system (Haken et al., 1985). That model became known as the HKB model (after the authors) and in retrospect became the fundamental formal construct for the dynamic systems theory of coordination proposed by Kugler and colleagues (1980) and Kelso and colleagues (1980). To describe nonlinear dynamics of the bimanual upper limbs, Haken and colleagues (1985) had to accomplish the following: (1) define a control and an order parameter;

(2) identify the presence of high entropy or an attractor state; and (3) define a coupled oscillator with two degrees of freedom for the two component parts (e.g., bimanual fingers or bimanual wrists).

The relative phase patterns of 0º and 180º were good candidates for the order parameter because relative phase reflected the coordination among the component parts with two degrees of freedom (e.g., bimanual fingers or bimanual wrists). The control parameter was the oscillatory frequency. The oscillatory frequency was an external variable imposed on the bimanual finger or wrist system. Haken and colleagues (1985) modeled the in-phase (0º) and the anti-phase (180º) targets as attractor states, considering variations of the control parameter. According to the HKB model (1985), when the complex, self-organizing system was in a less stable pattern and the control parameter was changed, the system was attracted to the more stable pattern. Furthermore, the change in the control parameter altered the potential attractor landscape to induce a phase transition from the less stable 180º pattern to the more stable 0º pattern. The HKB model (1985), therefore, was able to describe the results of Kelso's (1981, 1984) experiments.

In summary, Newtonian mechanics are adequate for describing predictable, linear trajectories of single bodies when initial conditions (i.e., position and velocity) are known. These Newtonian trajectory approximations, however, begin to break down when initial conditions of single bodies are unknown and when the behavior of interconnected parts of a dynamic system is studied. Thermodynamic principles, therefore, more adequately describe the macroscopic features of dynamic systems with many coordinative components. According to Clausius's second law of thermodynamics, a dynamic system is gradually drawn to an attractor state or a state of high entropy. External energy sources or control parameters acting upon the complex system, however, can induce a variety of behavior patterns or order parameters. Bernstein's (1967) degrees of freedom problem prompted investigation into the identification of functional synergies within the human body (Arutyunyan et al., 1969; Gurfinkel et al., 1971; Shik & Orlovski, 1976) and the self-organization of such functional synergies for movement output (Haken et al., 1985; Kelso, 1981, 1984).

Kelso (1981, 1984) subsequently applied nonlinear dynamic concepts to the motor behavior of bimanual finger and wrist movements. From the experiments, results indicated that a 0º relative phase pattern and a 180º relative phase pattern are attractor states. The 180º pattern, however, became unstable at higher oscillatory frequencies due to a change in the control parameter. This instability led to a phase transition from the 180º pattern to the more stable 0º pattern. Once the phase transition was achieved, the subjects failed to return to the 180º pattern indicating a change in the attractor landscape due to the control parameter (Kelso, 1981). The theoretical HKB model (1985) was developed by Haken, Kelso, and Bunz to describe and replicate the behavioral results of the Kelso (1981, 1984) experiments. This model offered a way of describing emerging patterns of coordination within a complex system as the patterns of coordination are pushed into non-equilibrium conditions by the control parameter.

1.1.7 Nonlinear Mathematical and Physical Dynamics Applied to Voice Production

As noted, dynamic systems theory of motor behavior involves the study of synergetics using the HKB model (1985) as the formal underlying framework. The study of non-linear dynamics, however, is a massive field with research in other biological systems grounded in non-linear dynamic principles of mathematics and physics rather than the HKB (1985) model (Ding, Tuller & Kelso, 1995; Lipsitz, 1995; Smith & Neale, 1994). Of interest for the present work is the use of nonlinear dynamics in voice science. Research on non-linear dynamics applied to voice production has primarily focused on mathematics and physics as the framework for such investigation as opposed to dynamic systems theory of motor behavior or the HKB (1985) model (Behrman, 1999; Behrman & Baken, 1997; Berry, Herzel, Titze, Story, 1996; Herzel, Berry, Titze & Saleh, 1994; Kelman, 1981; Mergell, Fitch & Herzel, 1999; Steinecke & Herzel, 1995; Tokuda, Riede, Neubauer, Owren & Herzel, 2002). Recently, nonlinear dynamics have been used to challenge traditional linear models of speech and voice production, according to which acoustic filter functions from the vocal tract are simply added to vocal fold output acoustics to produce the acoustic output at the mouth (Fant, 1960). Challenges to the linear model have come in the form of data indicating interactive and thus nonlinear relations between subglottal acoustics and vocal fold behavior (Austin & Titze, 1997) and between vocal tract acoustics and vocal fold behavior (Titze, 2002). One scientist, however, investigated voice production from the foundation of the dynamic systems theory of motor behavior and her work will be discussed in a later section (Steinhauer, 2001).

Even without dynamic systems theory of motor behavior or the HKB (1985) model as the framework, the non-linear, mathematical and physical investigation of voice production emphasizes the concept of stability. For the movement scientist with the HKB (1985) model as a theoretical foundation, stability or lack of stability of a dynamic system is demonstrated through behavioral data (Kelso, 1981, 1984). In contrast, the scientist studying voice production from a non-linear mathematical and physical framework superimposes behavioral data onto mathematical equations for a measure of stability (Behrman, 1999; Behrman & Baken, 1997). The method of stability analysis is different between the two frameworks; however, the goal of determining the stability properties of a dynamic system remains the same.

The application of non-linear dynamics to voice production was intended to mathematically characterize normal and abnormal vocal fold vibration from data obtained by laryngeal stroboscopy, excised larynges, and human subjects. Laryngeal stroboscopy revealed that various voice pathologies produced irregular vibratory patterns of the vocal folds resulting in a rough voice quality (Hirano, 1989). Researchers, therefore, have performed experiments with excised human and animal larynges to observe vocal fold movement by a strobe light during different adduction and elongation patterns of the vocal folds (Berry et al., 1996; Kelman, 1981; Tokuda et al., 2002). Observations of vocal fold vibration were made for various subglottal pressures during asymmetric adduction and elongation of the vocal folds. Human subject data involved microphone and electroglottography (EGG) signals during sustained /a/ phonations (Behrman, 1999; Behrman & Baken, 1997) and narrow-band spectrograms for the sustained vowels /e/ and /i/ (Herzel et al., 1994). Both healthy subjects with no laryngeal pathology and subjects with laryngeal pathology were used in data collection. From the experimental data obtained by laryngeal stroboscopy, excised larynges, and human subjects, researchers analyzed the data within a mathematical, non-linear dynamic framework (Behrman, 1999; Behrman & Baken, 1997) or devised computational models to represent normal and abnormal vocal fold vibration (Herzel et al., 1994; Mergell et al., 1999; Steinecke & Herzel, 1995).

A focus of the mathematical, non-linear dynamic framework involves the identification of possible states of a dynamic system called phase space. The phase space specifies the system completely by knowing how the system will function in the immediate future. The patterns of behavior that exist in the phase space can be finite (e.g., two states for the ideal coin toss, head or tails) or infinite (e.g., all real numbers as possible states) (Coveney & Highfield, 1990; Gleick, 1987; Hale & Kocak, 1991). For example, Behrman and Baken (1997) embedded EGG data within the infinite phase space for production of the sustained /a/ vowel at a comfortable pitch and loudness level. The embedding of the EGG data followed methods by Takens (1981), in which reconstruction of the attractor was accomplished using the method of lag variables. Once the EGG data were embedded, the correlation dimension was estimated (Behrman & Baken, 1997). The correlation dimension is an estimate of the complexity or irregularity of a system in space or time, which provides information about the number of dimensions required to describe the attractor (Barnsley, 1988; Grassberger & Procaccia, 1983; Mandelbrot, 1983). The estimation of the correlation dimension from the embedded EGG data was used for an ultimate goal of approximating the minimum degrees of freedom required to describe healthy and dysphonic phonation (Behrman & Baken, 1997). Although the correlation dimension appeared generally consistent for the healthy subjects, results indicated that the correlation dimension for the subjects with vocal fold pathologies was highly variable and should be interpreted with caution when approximating system dynamics for dysphonic behaviors of the phonatory system.

The term “degree of freedom”, used in mathematical and physical investigations of dynamic systems, usually refers to a single coordinate dimension of the phase space. For example, Titze (1994, 1976) modeled healthy vibration as a coupled 11 mode oscillator with two degrees of freedom for each coordinate dimension of the phase space, which corresponded to one degree of freedom in the antero-posterior plane and one degree of freedom in the inferior-superior plane. Conversely, Bernstein’s (1967) definition for “degree of freedom” involves the number of component parts within a dynamic system contributing to the synergistic production of a functional gesture. For example, Kelso (1981, 1984) identified two degrees of freedom for the production of bimanual relative phase patterns (i.e., one degree of freedom for the right hand and one degree of freedom for the left hand). This discrepancy in definitions can lead to confusion and it is advisable to check which meaning of the term is intended in a particular context.

In a subsequent study, Behrman (1999) did not investigate the correlation dimension for healthy subjects and subjects with laryngeal pathology. Instead, the global embedding dimension and local dynamical dimension were calculated from both microphone and EGG signals during sustained phonation of /a/ for 5 healthy subjects and 7 subjects with laryngeal pathology. The calculation of the global embedding dimension was used to unfold the attractor in a multi-dimensional phase space. The calculation of the local dynamical dimension was used to approximate the dominant degrees of freedom of the unfolded attractor. The purpose of the Behrman (1999) study was to initially classify different vibratory modes of the vocal folds by the calculation of the global embedding dimension and the local dynamical dimension. The data, however, did not reveal consistent differences in degrees of freedom between healthy and pathologic phonation or between different vibratory modes of pathologic phonation. The local dynamical dimension suggested that the pathologic vocal fold vibration was governed by a low number of dominant degrees of freedom.

In conclusion, the non-linear, mathematical investigations into the stability properties of the voice production system for healthy subjects and subjects with laryngeal pathology appear to be inconclusive (Behrman, 1999; Behrman & Baken, 1997). The calculation of the correlation dimension from EGG signals during sustained /a/ productions was highly variable in subjects with laryngeal pathology (Behrman & Baken, 1997). Consequently, Behrman (1999) attempted to distinguish normal phonation from pathologic phonation by calculating global embedding and local dynamical dimensions during microphone and EGG signals of sustained /a/ productions. The data indicated no significant difference between normal and pathologic phonation (Behrman, 1999). The application of non-linear, mathematical and physical dynamics to voice production by superimposing behavioral data onto mathematical equations has not consistently produced distinctions between normal and pathologic phonation (Behrman, 1999; Behrman & Baken, 1997). This inability to distinguish between normal and pathologic phonations may be due to the method of analysis by superimposing behavioral data onto mathematical equations for determining the stability properties of the dynamic system. Perhaps the stability properties of a dynamic, biological system should be investigated by real-time behavioral data with the possible attractor landscape identified before beginning the analysis and collecting the data. The proposed studies outlined in a later section will attempt to investigate the stability properties of the limb system and the voice production system by real-time behavioral data with a known potential attractor landscape.

1.2 DYNAMIC SYSTEMS THEORY APPLIED TO MOTOR BEHAVIOR AND THE HKB (1985) MODEL: PREDICTIONS AND LIMITATIONS

As previously discussed, the application of nonlinear dynamics to motor behavior originally involved a theory of motor coordination (Haken et al., 1985; Kelso, 1981, 1984; Schmidt & Fitzpatrick, 1996). According to dynamic systems theory, control of a motor behavior involves the coupling of relevant coordinative movement structures so that synergy is attained among the component parts (Schmidt & Fitzpatrick, 1996). The concept of a motor program or central executive, which is central to schema theory, an alternative theory of motor control and motor learning (Schmidt, 1975; 1976; 2003), plays no clearly discernible role in the dynamic systems theory of motor behavior. Rather, emphasis is placed on solving the "degrees of freedom" problem of how the motor system organizes itself to perform complex movements without control from a central executive (Bernstein, 1967). According to Bernstein (1967), when two or more independent moving degrees of freedom combine to produce one functional gesture, the independent parts are coupled to form a coordinative structure. This coupling, hypothesized by Bernstein (1967) to solve the degrees of freedom problem, occurs at the biomechanical system with no influence from the central executive. Dynamic systems theory only later addressed motor learning. For example, Zanone and Kelso (1992) suggested that improvement in the production of an action is achieved by optimization of the synergy between the component parts of a complex moving system.

In more recent years, Haken, Kelso, and Bunz (1985) formulated the "HKB" model to provide a systematic foundation for theoretical constructs of dynamic systems theory in motor behavior. As noted, this model linked the concepts of thermodynamics (Briggs & Peat, 1989; Coveney & Highfield, 1990; Gleick, 1987; Prigogine & Stengers, 1984), pattern formation in complex systems far from equilibrium (Haken, 1977, 1984, 1988), and coordinative structures of human movement (Kelso, 1981, 1984) to a theory of motor control involving nonlinear dynamic system principles and concepts. To apply the dynamic systems theory to motor behavior, the HKB model (1985) had to combine elements of nonlinear dynamic systems as they relate to human movement. The elements included: non-linear behavior, dynamic systems, control and order parameters, and stability properties. The HKB model (1985), therefore, has two levels: (1) a potential, which describes the stability properties of relative phase between two limbs and (2) a nonlinear system of coupled or synergistic oscillators, which relates these potentials to individual limb movements and their interactions.

Within the potential level, control and order parameters are defined for a coordinated movement system. The control parameter is any external variable that may influence the system or push it towards a change in behavior pattern that is not inherent within the complex system (e.g., increasing speed of oscillation is a control parameter; Haken, 1984, 1988). The order parameter is the index along which behavior patterns emerge out of a dynamic system (e.g. relative phase between the two limbs; Haken, 1984, 1988). A behavior pattern that occurs spontaneously is said to function as an *intrinsic dynamic* if it is inherent to the system without the need for a control parameter to influence its pattern of behavior (Kelso, 1995). Intrinsic dynamics correspond to the attractor landscape of the order parameters. The HKB model (1985) specifically addressed the moving nonlinear system as bimanual finger or wrist gestures. The order parameters, therefore, are the relative phase patterns between the bimanual effectors.

The stability properties of the relative phase patterns are identified by the potential movement pattern landscape and the amount of variability inherent to the movement pattern landscape (Haken et al., 1985). For example, a stable attractor state or a state of high entropy would be characterized by a small region in the potential movement landscape with limited variability. Conversely, an unstable pattern of low entropy or a non-attractor state would be characterized by a large region in the potential movement landscape with greater variability. In summary, the potential level of the HKB model has the ability to describe the stability properties of relative phase with influences from a control parameter.

The second level of the HKB model (1985) is the nonlinear system of coupled oscillators. This coupled oscillator level relates the potential level to individual limb movements and their interactions. The limbs were modeled as self-organized oscillators with two degrees of freedom; one degree of freedom for one limb and the other degree of freedom for the other limb. The

HKB (1985) model coupled the two limbs through their changing amplitudes as the control parameter (e.g., frequency or oscillatory changes) was varied. It was important that the model include coupling of the two limbs because the experiments by Kelso demonstrated phase transitions from a less stable pattern (e.g., 180° relative phase,) to a more stable pattern (e.g., 0° relative phase) based on amplitude changes between bimanual finger and bimanual wrist gestures (Kelso, 1981, 1984). For example, the phase transition and loss of stability at oscillatory frequencies above 2.25 Hz for the 180º pattern was characterized by a decrease in amplitude between the coupled limbs (Kelso, 1981, 1984).

Learning, within the context of the HKB model (1985), is viewed as a pattern formation process in which the learner acquires new coordination patterns on the background of already existing patterns. Existing patterns refer to the intrinsic dynamics of a complex system that are inherent to the individual without the need for environmental influences. In Kelso's experiments (1981, 1984), subjects were asked to perform 0° and 180° patterns with no guidance or with special instructions provided once the task began. In the in-phase or 0º relative phase pattern, the fingers or the wrists moved toward each other and then away from each other continuously with the same homologous muscle groups contracting at the same time (Kelso, 1981, 1984). In the anti-phase or 180º relative phase pattern, the fingers or wrists moved together in a parallel fashion with the homologous muscle groups contracting in an alternating fashion (Kelso, 1981, 1984). Kelso (1981, 1984) concluded that the behavior exhibited by the subjects was primarily due to each subject's intrinsic dynamics. Visual feedback, however, was present in the experiment. The subjects were able to visualize their finger and wrist movements and to know the positioning of the fingers and wrists in space from visual feedback. With the presence of the visual feedback, it is difficult to conclude that the 0° and 180° patterns were inherently produced as intrinsic dynamics without influences external to the moving limbs.

The HKB model (1985) considered only two degrees of freedom representing the two limbs. No other additional external influences were included that could potentially influence movement output. Additional external influences for the production of movement might have included feedback from the periphery. The control parameter within the potential level of the HKB model (1985) accounts for all necessary external or environmental influences, thereby rendering top-down allowances to the dynamic system unnecessary. The original HKB (1985) model has been expanded to include influences from external variables (Peper, Beek & Daffertshofer, 2000; Schöner & Kelso, 1988a, 1988b); however, intrinsic dynamics are still considered to be spontaneous to a moving system without the need for external influences (Kelso, 1995, Wallace, 1996).

In summary, dynamic systems theory positions itself as a theory of motor coordination (Haken et al., 1985; Jeka & Kelso, 1989; Wallace, 1996). Applied to many domains within contemporary science (Camazine, Deneubourg & Franks, 2001), this theory describes human beings as self-organizing systems capable of stability and coordination in the production of movement. Movement patterns are seen as an emergent set of relations among the coordinated movement system. What is organized, therefore, is a set of physically encoded intrinsic dynamics of a coordinated movement system rather than a motor program governing movement output (Haken et al., 1985; Jeka & Kelso, 1989). A movement pattern may change temporarily or permanently depending upon the dynamic interaction between the component body parts and the control parameter influencing the system. Inherently stable patterns that emerge out of coordinative structures are called *attractor states*. Motor learning is seen to involve a breakaway from existing, intrinsic attractor states towards novel, learned patterns (Schöner, Zanone & Kelso, 1992; Wallace, 1996; Zanone & Kelso, 1992, 1997). The movement process is characterized by a temporary increase of within- and between-trial variability until a new attractor state is established (Kelso, 1995; Wallace, 1996).

1.2.1 Predictions of Dynamic Systems Theory of Motor Behavior

One prediction of dynamic systems theory of motor control and learning is that attractor and non-attractor states can be identified in coordinated, self-organizing complex movement systems. According to the second law of thermodynamics, a complex system may evolve from a state of energy exchange or low entropy among its component parts to a state of no energy exchange or high entropy condition (Briggs & Peat, 1989; Coveney & Highfield, 1990; Gleick, 1987; Prigogine & Stengers, 1984). The high entropy condition is often referred to as equilibrium or an attractor state. Two types of attractor states are discussed in the motor behavior literature: a point attractor, in which all behavior patterns of a complex system are drawn to a single point, and a periodic or limit cycle, in which all behavior patterns of a complex system are drawn to an area of attraction (Schmidt & Fitzpatrick, 1996; Turvey, 1990).

Support for the prediction that attractor states exist in coordinated, self-organized movement systems comes primarily from literature on two classes of coordinated limb movement; rhythmic and discrete. Using the measurement tools for the identification of attractor states, motor behavior researchers have identified coordinated interlimb rhythmic movements as a movement class in which dynamic principles of self-organization are operating. This movement class has been characterized to possess two point attractors corresponding to the in-phase (0º) and anti-phase (180º) relative phase patterns (Amazeen, Sternard & Turvey, 1996;

Haken et al., 1985; Kelso, 1981, 1984; Peck & Turvey, 1997; Schmidt, Beek, Treffner & Turvey, 1991; Schmidt, Fitzpatrick, Bienvenu & Amazeen, 1998; Schmidt, Shaw & Turvey, 1993; Sternard & Amazeen, 1996; Yamanishi, Kawato & Suzuki, 1980) (See Figure 1). Discrete movements in which a limb segment is brought to a specific point in space have also been characterized as having the dynamics of point attractors (Feldman, 1986; Kugler et al., 1980; Schöner, 1990). In addition, other researchers have identified 45°-phase, 90°-phase, and 135°-phase patterns as point non-attractor states in interlimb rhythmic movements (Fontaine, Lee & Swinnen, 1997; Liao & Jagacinski, 2000; see Figure 1). Periodic or limit cycle attractors have been demonstrated in rhythmic movements in which a limb segment is oscillated about a joint in a pendulum swinging movement (Beek & Beek, 1988; Kay, Kelso, Saltzman & Schöner, 1987; Peck & Turvey, 1997).

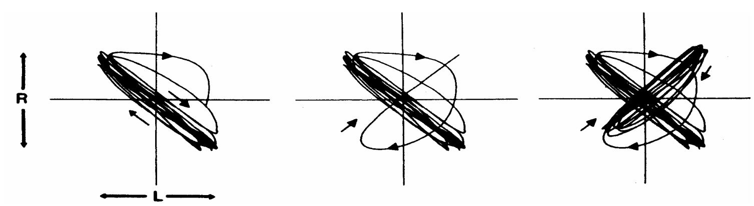

Figure 1. Lissajous plots from Kelso (1984). Relative spatial location of right and left hands is displayed on *ordinate* and *abscissa*, respectively, during a bimanual task. Viewed from left to right, hands first demonstrate an attractor state pattern that becomes more variable over time as a non-attractor state is approached. Reprinted by permission from American Physiological Society via Copyright Clearance Center: *American Journal of Physiology*, 15, R1000-R1004, copyright (1984).

Additionally in the motor behavior literature, two methods have been identified for measuring the degree of attraction within a nonlinear dynamic system. In the first method, the potential attractor landscape must be known within a set of coordination patterns (Schmidt & Fitzpatrick, 1996; Turvey, 1990). The potential attractor landscape is then dependent upon the degree of variability within the production of the coordination patterns (Schmidt & Fitzpatrick, 1996; Turvey, 1990). If the field of a potential attractor is large with great variability, then the dynamics of the coordination patterns will have a relatively weak attractor region. In contrast, if the field of a potential attractor is small with minimal variability, then the dynamics of the coordination patterns will have a strong attractor region. In the second method, attractor states can be measured by the relaxation time of the system –that it, the time it takes the system to return to equilibrium following the influence from a control parameter (Schmidt & Fitzpatrick, 1996; Turvey, 1990).

A second prediction in the dynamic systems theory of motor behavior is that the learning of movement patterns involves a period of instability among the order parameters as an existing behavior pattern is escaped and another is approached (Kelso, 1995; Schöner et al., 1992; Wallace, 1996; Zanone & Kelso, 1992, 1997). The initial behavior patterns are likely to include conditions of high entropy or attractor states and conditions of low entropy or non-attractor states (Haken et al., 1985). In studies supporting this prediction, subjects were asked to perform several cyclic patterns across bimanual fingers or wrists (Schöner et. al., 1992; Zanone & Kelso, 1992, 1997). In a study by Schöner and colleagues (1992), the cyclic patterns included 3 relative phase patterns; a 0° in-phase pattern (e.g. the fingers move toward and then away from each other), a 180° anti-phase pattern (e.g. the fingers move in a parallel motion), and a 90° phase pattern intermediate to the in-phase and anti-phase patterns. During practice, the 90° pattern was unstable with increased variability and characterized as a non-attractor state, whereas the 0° pattern and the 180° pattern were identified as attractor states. After practice, however, the 90° pattern achieved greater stability, whereas the 180° pattern destabilized and the 0° pattern remained unchanged.

A modification of the attractor states occurred by a strengthening of the dynamics for the 90° pattern while weakening the strength—or “pull” of the 180° pattern (Schöner et al., 1992).

Subjects learned how to escape from existing attractor states to approach the novel 90° pattern. This effect was seen in the destabilization of the 180° pattern, while performance improved on the novel 90° pattern. Increases in pattern stability are taken to indicate learning of a task, formulations of new attractor landscapes, and also transfer of learning to novel conditions (Schöner et. al., 1992; Zanone & Kelso, 1992, 1997).

In conclusion, dynamic systems theory of motor behavior predicts the existence of attractor states among the components of a complex moving system. These attractor states correspond to the intrinsic dynamics that a learner brings to a given motor task. Learning of new movement behaviors occurs on the foundation of already existing patterns. The learning process is characterized by phase transitions due to a loss of stability in one pattern and a strengthening of stability in another. The HKB model (1985) of dynamic systems theory has brought the self-organizing properties of the neuromuscular system to the forefront of motor control and motor learning.

1.2.2 A Limitation of Dynamic Systems Theory of Motor Behavior addressed by Expansion of the Original HKB (1985) Model

A limitation of the original HKB (1985) model and dynamic systems theory applied to motor behavior is the limited consideration of cognitive influences in motor control and behavior. In recent years, however, researchers have investigated the cognitive influences of intention, attention, perception, and sensory feedback on bimanual coordination. The most recent investigations are discussed in the following sections.

The HKB model (1985), in its rudimentary form, did not directly address the role of cognitive influences in motor control. The obvious challenge is that cognition does play a role in motor performance and learning. The clearest evidence to this effect arises from findings about the role of intention on motor performance and learning (Amazeen, Amazeen, Treffner & Turvey, 1997; Carson, Byblow, Abernathy & Summers, 1996; Carson, Goodman, Kelso & Elliott, 1994; Fontaine et al., 1997; Lee, Blandin & Proteau, 1996; Riley, Amazeen, Amazeen, Treffner & Turvey, 1997; Scholz & Kelso, 1990; Swinnen, Dounsakaia, Walter & Serrien, 1997, Swinnen, Jardin & Meulenbrock, 1996; Swinnen, Lee, Verschueren, Serrien & Bogaerts, 1997; Wuyts, Summers, Carson, Byblow & Semjen, 1996; Zanone & Kelso, 1992, 1997). To adapt the HKB model (1985) to account for both intentional influences and learning, Schöner and Kelso (1988a, 1988b) proposed an additional term or degree of freedom to the original HKB equation. Specifically, they added an attractor force called "behavioral information" to the model. Behavioral information refers to influences of intention, the environment, and learning. Such information may influence the order parameters of a complex moving system.

Another group of researchers identified the absence of cognitive influences in the control of movement as a shortcoming of the original HKB (1985) model (Peper, Beek & Daffertshofer, 2000). To account for cognitive influences on movement output in the original HKB (1985) model, Peper and colleagues (2000) incorporated a 4-oscillator model with 4 degrees of freedom. The 4 degrees of freedom included the 2 limbs as 2 degrees of freedom with an additional 2 degrees of freedom to account for cognitive influences. The limbs communicate with cognition via a feedback function. Adaptations, therefore, have been made to include cognitive influences in the original HKB (1985) model. The specific role of cognition, however, remains vague in the model.

1.2.3 Limitations of Dynamic Systems Theory of Motor Behavior: Support from Neurophysiological and Behavioral Research

1.2.3.1 Recent neurophysiological research pointing to a dynamic heterarchy of nervous system organization and function.

The classical, early 20th century views that sensory input is necessary for motor output (Sherrington, 1906) and that the nervous system is controlled by a top-down hierarchy (Jackson, 1870s; for review, Walsh, 1961) represent a stark contrast to current views of nervous system organization and function. By the second half of the 20th century, modern views of nervous system function fueled a conceptual transition. This transition to modern theories and concepts was characterized by views around a distributed heterarchy of nervous system function in which neurons may have differing functions depending upon dynamic changes in the neuronal network (Davis, 1976), hierarchical and horizontal organization of information-processing (Guillery & Sherman, 2002; Jones, 2001; Mountcastle, 1979), selective enhancement of neurons through interactions with the environment (Edelman, 1987), and transient binding of neuronal activity that underlies human perceptions and behaviors (Crick & Koch, 1990).

Considering current views of nervous system organization and function, both the relatively top-down model of schema theory (Schmidt, 1975, 1976) and the relatively bottom-up model of dynamic systems theory (Haken et al., 1985; Jeka & Kelso, 1989; Wallace, 1996) fail to account for the complexity and sophistication of mammalian behavior. One alternative approach to motor control and learning based on neurological foundations was described by Crick and Koch (2003) in their "framework of consciousness" model. It is widely known that rather than operating according to a strict hierarchical processing structure, neuronal coalitions are distributed in a heterarchical network with both horizontal and hierarchical projections formed by past associations and expected consequences of movements (Crick & Koch, 2003).

These neuronal coalitions are shaped by both motor and sensory operations. Stated differently, the neuronal system is not strictly dedicated to a hierarchical organization or a horizontal organization, but rather both sensory and motor functions play an integral role in a heterarchical distribution of neuronal coalitions.

An example from visual processes is as follows. The visual sensory cortex is arranged in a semi-hierarchical fashion with influences from both hierarchical and horizontal neuronal coalitions (Crick & Koch, 2003). A stimulus travels up the visual cortex without emerging in consciousness through the dorsal and ventral stream, where it then moves back down through the visual cortex and is expressed in consciousness (Crick & Koch, 2003). Top-down processing is suggested behaviorally by evidence of people "seeing" missing portions of incomplete images such as faces or other objects (Crick & Koch, 2003). There are, however, many horizontal projections within the visual system suggesting a semi-hierarchical function with influences from horizontal neuronal connections (Crick & Koch, 2003).

Additional support against a strict bottom-up or top-down processing of the central nervous system comes from data from the thalamus where motor and sensory functions converge in the brain. According to Jones (2001), the matrix and core cells within the thalamus have a variety of cortical projections that provide both columnar activation (i.e., hierarchy) and horizontal spreading activation. The matrix cells project to the superficial layers of cortex in a horizontal, spreading activation fashion, whereas the core cells project to the middle layers of cortex in a topographic fashion (Jones, 2001). According to Guillery and Sherman (2002), past theories of the thalamus as only a mediator of sensory input to cortex is an oversimplification. Evidence from rats suggests that axons that originate in motor, somatosensory, and visual cortex and terminate in the thalamus are branches of long descending axons that go to or through the brainstem. Messages that the thalamus relays to the cortex are also going to brainstem and, therefore, relate directly or indirectly to motor function. The thalamus-cortex-brainstem connections represent the dynamic relationship of sensory messages to ongoing motor circuitry.

This dynamic relationship between sensory and motor function points to a distributed heterarchical network among neuronal coalitions. Neuronal coalitions are linked together by a synchrony of firing among the summed action potentials. Crick and Koch (1990, 2003) postulated that the binding of neuronal coalitions occurs by the spread of rhythmicity (i.e., 40 Hz oscillations) or synchrony within neuronal firing rates. The binding of neuronal coalitions at 40 Hz oscillations assists in the selection and control of information that underlie perceptions and behaviors. One theory proposes that the neural activity that represents the stimuli or events to be selected for attentional allocation is selected through modification of its synchrony (Crick & Koch, 2003). In the neural mechanism of selective attention, information that is selected for attention is made more prominent by synchrony of neuronal firing rates, whereas information that is ignored is made less prominent by asynchrony of neuronal firing rates. Action potentials that arrive synchronously at a neuron summate to evoke larger postsynaptic potentials than do action potential that arrive asynchronously (Crick & Koch, 2003; Hsiao, O'Shaughnessy & Johnson, 1993; Niebur, Hsiao & Johnson, 2002). Synchronous action potentials, therefore, have a greater effect at the next processing stage than do asynchronous action potentials.

Evidence relating synchrony of firing to selective attention comes from neurophysiological studies of neurons in the somatosensory cortex of macaque monkeys receiving single- and multi-unit recordings. In one study (Hsiao et al., 1993), two monkeys were trained to switch their attentional focus between visual and tactile stimuli in discrimination tasks. In the tactile task, the animals were required to identify embossed letters of the alphabet with constantly changing letter targets. In the visual task, the animals received the same tactile stimulation while detecting the dimming of a square on a screen. When the monkeys performed the identification task under tactile conditions, 70% of the neurons were in synchrony. Conversely, with the addition of the visual task to the tactile task, only 43% of the neurons remained in synchrony. Coalitions of neurons, therefore, were more synchronous when the monkeys only had to perform the tactile task. With the addition of the visual task to the tactile task, synchrony of firing decreased due to competition with other neuronal coalitions for the perception of the visual stimuli. Changes in attentional focus may increase the synchrony of firing in some neuronal coalitions and may decrease it in other neuronal coalitions.

In a heterarchy of motor and sensory dynamics, there is no fixed chain of command or informational flow; instead the flow is flexible and dependent upon the context of an event, allowing different cortical areas to take priority under different behavioral constraints (Kalaska & Crammond, 1992). Moreover, representations of various movements can occur concurrently in a heterarchy thereby illustrating the difficulty of determining functionality among component parts within the distributed system (Kalaska & Crammond, 1992).

Even though net information flow can exist across the cortical and subcortical areas, differences in the timing of movement-related activity are routinely observed depending upon task demands and behavioral circumstances (Kalaska & Crammond, 1992). Such subtle timing difference within a distributed heterarchy may be relevant for the production of varying types of skilled movements. It has been hypothesized that 40 Hz oscillations are evident among neuronal networks during conscious sensorimotor transformations and other cognitive processes (Crick & Koch, 1990, 2003). Neurons in a distributed network are transiently coupled by synchronous discharge that binds the population together relative to the sensorimotor task at hand (Crick &

Koch, 1990, 2003). The 40 Hz oscillations within local sensory networks and global networks across motor, sensory, and association areas have been correlated with perceptual and behavioral performance (Crick & Koch, 1990, 2003). Without timing of neuronal discharge relevant to movement constraints and behavioral circumstances, the distributed heterarchy of the sensorimotor system would fail to perform as an optimal controller and processor (Crick & Koch, 1990, 2003).

In summary, neuronal coalitions distributed in a heterarchical fashion with both vertical and horizontal projections point to a dynamic relationship between sensory and motor function in the human nervous system. The historical notion of a clear division between sensory and motor function in a purely hierarchical fashion cannot explain current neurophysiological evidence. Clear examples relate to the thalamus, which is not just a sensory mediator to cortex, but a dynamic sensory and motor mediator to cortex and ongoing motor activity (Jones, 2001; Guillery & Sherman, 2002). Additionally, the core and matrix cells of the thalamus bind together in a vertical and horizontal fashion across the cortex, suggesting a distributed function of motor and sensory dynamics (Jones, 2001). The binding of neuronal coalitions at 40 Hz oscillations enables synchrony of firing among action potentials which correlates with selective attention and also a distributed, heterarchical network of motor and sensory system dynamics (Crick & Koch, 1990, 2003; Hsiao et al., 1993; Niebur et al., 2002).

1.2.3.2 Recent evidence for the role of attention in bimanual coordination.

The foregoing studies demonstrate that although dynamic systems theory of motor behavior has traditionally focused on biomechanical synergistic influences in movement, increased interest has been seen in recent years on cognition and its impact on dynamic moving systems. Particular attention has been given to the role of attention for bimanual coordination performance and learning (Carson, 1996; Fuchs & Kelso, 1994; Jirsa, Fuchs & Kelso, 1998; Kelso, 1997; Monno, Chardenon, Temprado, Zanone & Laurent, 2000; Schöner & Kelso, 1988a, 1988b; see also Schmidt, 2003; Temprado, Zanone, Monno & Kelso, 2002; Temprado, Zanone, Monno & Laurent, 1999; Zanone, Monno, Temprado & Laurent, 2001; Zanone, Temprado & Monno, 1999).

In a series of studies, Temprado and colleagues investigated the attention or cognitive effort involved in the in-phase pattern or attractor state versus the anti-phase pattern or near-attractor state for bilateral limb movements (Monno et al., 2000; Temprado et al., 2002; Temprado et al., 1999; Zanone et al., 2001; Zanone et al., 1999). Across the studies, attention was measured using a dual-task paradigm, in which subjects were instructed to attend to either the bimanual coordination task or a simultaneous secondary task, or both. Reaction time results from an initial study showed that the anti-phase or near-attractor state was dependent on cognitive effort, whereas little cognitive effort was seen for the in-phase or attractor state (Temprado et al., 1999). Similar findings were reported for two studies showing that cognitive resource allocation for attention was directly related to the degree of stability of a relative phase pattern in a bimanual task (Zanone et al., 2001, 1999). For example, the highly stable in-phase pattern or attractor state consumed less cognitive resources than the somewhat stable anti-phase pattern or near-attractor state (Zanone et al., 2001, 1999). According to another study, when cognitive resources for attention were allocated to a bimanual task, transitions from one pattern to another were delayed (Monno et al., 2000). Finally, in another study, attentional resources associated with an anti-phase pattern or near-attractor state decreased following bimanual training (Temprado et al., 2002).

The general point made from these studies on attention and bimanual coordination is that the allocation of attentional resources to motor performance depends upon the inherent stability of the task; unstable tasks require resources, whereas stable tasks appear to require little if any resources. The studies are important because they are among the first to address and specifically pursue specific cognitive mechanisms within a dynamic systems framework of motor performance and learning.

1.2.3.3 Recent evidence for the role of perception in bimanual coordination.

Another group of researchers challenged the lack of cognitive influences in the original HKB (1985) model by investigating the role of perception in the organization of voluntary movement (Mechsner, Kerzel, Knoblich & Prinz, 2001). Based on results from a series of three experiments, Mechsner and colleagues (2001) suggested that the more stable 0° in-phase pattern during bimanual finger oscillations, bimanual four-finger tapping, and bimanual circling patterns is related to perceptual rather than motoric movement goals. That is, the bias towards the 0° in-phase pattern is actually oriented towards spatial, perceptual goals without regard to the muscles involved. The perceptual goals are shaped by visual and proprioceptive feedback. This switch in emphasis to perceptual movement goals stands in direct contrast to the traditional view that the tendency towards the 0° in-phase pattern is due to a bias in co-activation of homologous muscles (Kelso, 1984; Johnson, Cunnington, Bradshaw, Phillips, Iansek & Rogers, 1998).

In the first experiment involving bimanual finger oscillation, the 0° in-phase pattern and the 180° anti-phase pattern were produced with congruous and incongruous hand positions (Mechsner et al., 2001; see Figure 2). In the congruous hand position, the perceptual goal of the 0° in-phase pattern (i.e., fingers moving toward and away from each other) was paired with the motoric goal of co-activation of homologous muscles. In the incongruous hand position, the perceptual goal of the 180° anti-phase pattern (i.e., fingers moving in parallel) was paired with the same motoric goal of co-activation of homologous muscles. If evidence was found to support the perceptual view of movement, then the perceived 0° in-phase action should always be more stable regardless of hand position. Conversely, if evidence was found to support the motoric view of movement, then the hand position with the co-activation of homologous muscles would be more stable regardless of the perceived relative phase pattern.

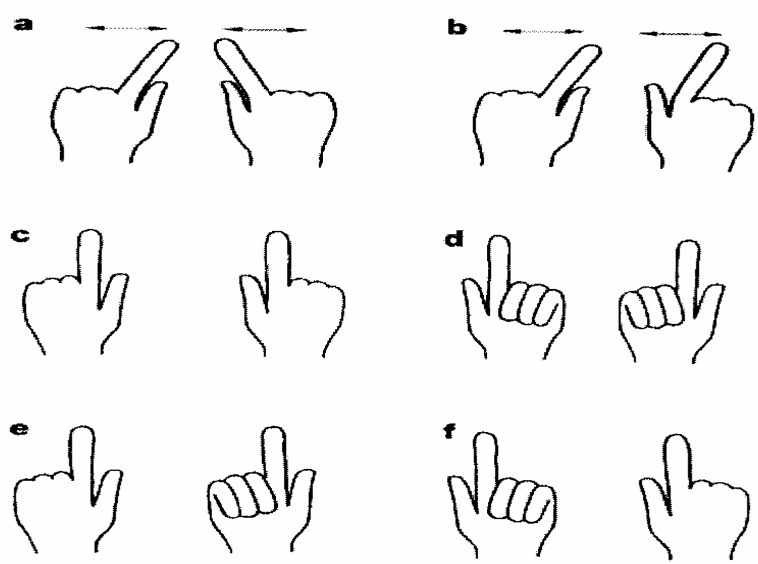

Figure 2. Hand positions and relative phase patterns. **a,** 0º in-phase pattern. **b,** 180º anti-phase pattern. **c, d,** Congruous positions with both palms up or both palms down. **e, f,** Incongruous positions with one palm up and the other palm down (Mechsner et al., 2001). Reprinted by permission from Macmillan Publishers Ltd: *Nature*, 414(1), 69-73, copyright (2001).

Eight, healthy subjects were asked to perform the movements with increasing frequency of oscillation from 1.4 Hz up to 3.6 Hz with visual feedback of the hands and without visual feedback of the hands. Results indicated that the perceived 0° in-phase pattern was always more stable regardless of the hand position, whereas the perceived 180° anti-phase pattern tended to disintegrate and performance switched to the 0° in-phase pattern at higher frequencies of oscillation. Evidence, therefore, was found to support the view that bimanual movements are least partly guided by perceptual goals rather than motoric goals involving the co-activation of homologous muscles. The pattern of results did not change when visual feedback of the hands was blocked.

In the second experiment with bimanual finger tapping, 10 healthy subjects were asked to perform 0° in-phase patterns and 180° anti-phase patterns with the index and middle fingers of both hands (Mechsner et al., 2001). The finger tapping was congruous when the finger combinations were identical for both hands and incongruous when the finger combinations were not identical for both hands. In the congruous finger tapping, the co-activation of the homologous muscles occurred for the 0° in-phase pattern, whereas, in the incongruous finger tapping, the co-activation of the homologous muscles occurred for the 180° anti-phase pattern. Subjects produced the patterns at increasing frequency of oscillations from 1 Hz up to 3 Hz with and without visual feedback of the hands. The results for the second experiment matched the results of the bimanual finger oscillation experiment. The 0° in-phase pattern was always the most stable regardless of the co-activation of homologous muscles, whereas the performance of the 180° anti-phase pattern switched to the more stable pattern at higher frequencies of oscillation. The authors, therefore, concluded that the more stable 0° in-phase pattern in bimanual finger tapping was not related to the motoric goal of co-activation of homologous muscles, but rather to perceptual goals.

In a third experiment, subjects were asked to perform bimanual circling patterns with two visible flags that were moved by two cranks hidden under a table (Mechsner et al, 2001; see Figure 3). The left flag circled directly above the left crank and hand, while the right flag circled in a 4:3 frequency ratio to the right crank and hand. The rationale for the frequency transformation in the right flag and right hand was that the 0° in-phase pattern and the 180° anti-phase pattern could not be visually predicted from the corresponding hand movement pattern. Consequently, no body-oriented strategy was possible to perform the two relative phase patterns because the relative phase patterns in the flags could not be predicted by the hand movement patterns. The performance of the 0° in-phase pattern and the 180° anti-phase pattern, therefore, was solely due to visual strategies. Eight healthy, subjects participated in the experiment. Subjects were instructed to begin each relative phase pattern at a slow pace and continue to increase velocity up to a point that they considered to be fast, but not beyond a point where control of the flags was lost. Results indicated that all subjects produced the 0° in-phase pattern as seen in the flags with increasing velocity. The 180° anti-phase pattern was also produced as seen in the flags, but performance became more variable with increasing velocity. From the results just described, the authors hypothesized that the tendency towards the more stable 0° in-phase pattern in bimanual coordination was purely perceptual.

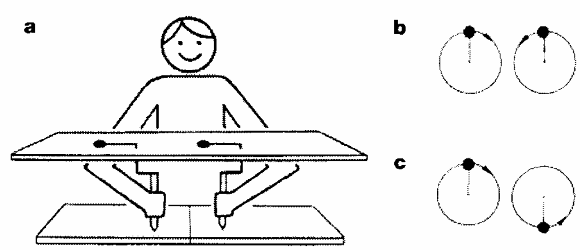

Figure 3. Apparatus used in the Mechsner and colleagues (2001) third experiment with the circling patterns. **a,** Apparatus. The subjects circled two visible flags by the cranks under the table. The left flag moved with the left hand whereas the right flag moved according to a well defined frequency transformation with the right hand. **b,** 0° in-phase pattern. **c,** 180° anti-phase pattern. Reprinted by permission from Macmillan Publishers Ltd: *Nature*, 414(1), 69-73, copyright (2001).

The hypothesis that the more stable 0° in-phase pattern in bimanual coordination is related to perceptual goals rather than motoric goals was supported by data from three experiments using bimanual oscillation, tapping and circling tasks (Mechsner et al., 2001) as well as by additional follow-up experiments involving a multi-finger tapping task (Mechsner & Knoblich, 2004). Another group of researchers attempted to replicate the findings of Mechsner and colleagues (2001, 2004) with a bimanual coordination pattern involving horizontal, linear movements at frequencies of 1.5 Hz and 2.0 Hz (Salter, Wishart, Lee & Simon, 2004). A congruent and an incongruent condition were used. In the congruent condition, the movement of the flags matched the movement of the arms. In the incongruent condition, the movement of the flags was opposite to the movement of the arms. Regardless of the condition, the subjects always performed the 0° in-phase with more stability than the 180° anti-phase pattern.

Salter and colleagues (2004) suggested that the stability of the 0° in-phase pattern across the congruent and the incongruent conditions provided support for a motor view of bimanual coordination rather than a perceptual view. The authors, however, suggested that task specificity provides some support for the perceptual view of motor coordination (Salter et al., 2004). For example, the bimanual circling patterns in the Mechsner and colleagues (2001) study were more dependent on visual feedback, whereas the linear bimanual patterns in the Salter and colleagues (2004) study were more dependent on proprioceptive feedback. This task-related difference between the availability of visual and proprioceptive feedback suggests that the perceptual and motor determination of coordination may be task specific. Future research is warranted to investigate the role of sensory feedback in the performance of coordination patterns as a function of task demands.

1.2.3.4 Recent evidence for the role of visual feedback in bimanual coordination.

It is generally acknowledged that one requires proprioceptive and visual information to fine tune motor patterns. Proprioceptive information from the periphery allows the central nervous system to monitor the moving limbs and to adjust the movement pattern if necessary. There is evidence that the coordination of ongoing movements uses proprioception in healthy subjects (see Cordo, Bevan, Gurfinkel, Carlton, Carlton & Kerr, 1995), while deafferentiated patients exhibit clear coordination deficits (Bonnard & Pailhous, 1999; Ghez & Sainburg, 1995; Jackson, Jackson, Husain, Harvey, Kramer & Dow, 2000; Jackson, Jackson, Newport & Harvey, 2002; Sainburg, Poizner & Ghez, 1993). Proprioception, however, cannot fully account for all motor coordination phenomena. Coordination deficits in deafferentiated patients become apparent only if vision is absent (Bonnard & Pailhous, 1999; Ghez & Sainburg, 1995; Jackson et al., 2002; Sainburg et al., 1993). The literature clearly suggests that visual feedback also plays a substantial role in motor coordination.

Positive evidence for the assumption that visual feedback does play a role in motor coordination comes from cyclical bimanual movements and discrete bimanual movements. Serrien and Teasdale (1996) asked young (i.e., age range 20-30 years) and older (i.e., age range 66-77 years) subjects to perform two cyclical bimanual coordination movements in the 0° in-phase and the 180° anti-phase mode with and without vision of the arms at a frequency of 1 Hz. Each trial lasted 15 seconds and 3 trials were conducted per condition. Results indicated that absence or presence of the visual feedback influenced the performance of the young subjects more than the older subjects (Serrien & Teasdale, 1996). That is, the stability of the young subjects' 0° in-phase pattern deteriorated when vision of the limbs was not available, whereas the young subjects' 180° anti-phase pattern became more stabile when visual information was absent (Serrien & Teasdale, 1996). It is interesting that the 0° pattern, the more stable of the two patterns, had greater stability with visual feedback, whereas the 180° pattern had greater stability without visual feedback. Since the 180° pattern is less stable than the 0° pattern, one would expect that increased sensory information would help to stabilize the pattern, but in fact the 180º pattern was destabilized. Regardless of the findings, the results suggest a role for sensory feedback in the control of the intrinsic dynamic for in-phase and anti-phase bimanual coordination patterns produced at a frequency of 1Hz.

Swinnen and colleagues (2000) investigated motor learning across practice in healthy adults and adults diagnosed with Parkinson's disease. Subjects were asked to trace triangles with both upper limbs at the same time across 22 practice trials lasting 20 seconds for each trail. An auditory metronome provided the pacing for completion of each side of the triangle at 500 ms. Vision was allowed at the start of practice; however, at the middle (i.e., after 10 trials) and at the end of practice (i.e., after 18 trials) two trials were completed in a blindfolded condition (Swinnen, Steyvers, Van Den Bergh & Stelmach, 2000). Feedback about movement speed and triangle accuracy was provided following every fifth trial. At initiation of practice, the typical signs associated with Parkinson's disease became evident, such as slower then normal movement productions. Moreover, reduced synchronization between the force-time specifications of both limbs was observed. When vision of the arms was withdrawn, subjects with Parkinson's disease showed a larger drift of tracing performance across the workspace. In spite of the difficulties just mentioned, the performance of subjects with Parkinson's disease did improve with the speed, consistency, and synchronization of movements as practiced continued. The subjects with Parkinson's disease, however, never reached the performance levels obtained in the age-matched control subjects.

In a study by Kazennikov and colleagues (2002), 16 healthy adult subjects performed a drawer-pull task with one hand opening the drawer while the other hand picked up a small peg in the drawer. All 16 subjects performed the task with visual feedback and without visual feedback in a blindfolded condition. In 12 of the 16 subjects, the task was performed easily after a few trials in the blindfolded condition; however, the task was slowed in comparison to the visual feedback condition (Kazennikov, Perrig & Wiesendanger, 2002). In 3 of the 12 subjects, the visual condition was performed with simultaneous movement of both the pull-hand for opening the drawer and the pick-hand for picking up the peg, whereas without vision the subjects delayed moving the pick-hand until the pull-hand grasped the drawer (Kazennikov et al., 2002). For 3 of the subjects, changing the sensory feedback constraints of a dynamic, moving system by withdrawing vision of the limbs changed the coordination pattern.

Cardoso de Oliveira and Barthelemy (2005) investigated the extent to which visual feedback shapes the coordination between the upper limbs in a discrete bimanual movement which involved hitting a small target with both index fingers in fast goal-directed movements. Subjects participated in a control condition that allowed visual feedback of both limbs and 3 subsequent experimental conditions that involved visual feedback of one of the limbs and a no visual feedback condition. Absence of visual feedback for one or both arms significantly increased reaction times for both arms and movement amplitudes for the occluded arm. When no feedback for either arm was available, trial-by-trial amplitude standard deviations were significantly higher than when feedback for one or both arms was present. From the results, the authors concluded that online visual feedback is used to shape the coordination between the two arms.

In conclusion, the preceding review provides evidence for the role of visual feedback in the control of bimanual coordination patterns. For example, the more stable 0° relative phase pattern had greater stability in the visual feedback condition, whereas the 180° relative phase pattern had greater stability without visual feedback (Serrien & Teasdale, 1996). Without vision of the arms, subjects with Parkinson's disease showed a drift in tracing performance as compared to healthy age-matched control subjects (Swinnen et al., 2000). In a drawer-pull task, a no vision condition resulted in a slower movement production with some subjects completely changing the coordination pattern to adapt to the lack of sensory information (Kazennikov et al., 2002).

Absence of visual feedback significantly reduced the reaction time of the upper limbs as well as the bimanual coupling of movement amplitudes (Cardoso de Oliveira & Barthelemy, 2005). Although the noted studies do suggest a role for visual feedback in bimanual coordination, the contribution of such feedback to the coordination dynamics of a bimanual limb task and a voice task has not been fully evaluated. Experiment 1 of the proposed series will investigate the role of visual and auditory feedback in the coordination dynamics for the bimanual coordination patterns of 0° and 180° at increasing frequency of oscillations. Experiment 2 of the proposed series will extend the investigation beyond the limb system to the voice production system to assess the generality of findings.

1.2.3.5 Limitations in methodology question preliminary evidence for attractor states in voice production.

To subscribe to a theoretical model of movement behavior, that theoretical model must have predictive abilities across a wide variety of movement behaviors. With the dynamic systems theory of motor behavior as a framework, Steinhauer (2001) hypothesized that attractor states exist in voice production, but due to limitations in methodology, the results of such experimentation must be analyzed with caution. The study presented below highlights the need for further investigation into the identification of attractor states outside the limb system.

Preliminary evidence for attractor states (i.e., inherently stable patterns) in voice production was provided in Steinhauer (2001). In her study, subjects with no singing background were asked to manipulate voice onset, voice quality, and fundamental frequency (Fo) while sustaining the vowel /i/. Subjects produced the 3 voice qualities of modal speech, mixed register, and falsetto across 3 voice onset conditions and 3 Fo conditions. The voice onset conditions were glottal, simultaneous, and breathy. The 3 Fo conditions were low, mid, and high frequencies. From these manipulations, evidence was expected to emerge for the existence of three attractor states: (1) glottal onset/speech quality/low Fo, (2) simultaneous onset/mixed quality/mid Fo, and (3) breathy onset/falsetto quality/high Fo. Trial stability was measured by percent correct productions across 72 acquisition trials, based on perceptual estimates from blinded listeners, and self-report of error for the trials. After adjusting for intensity, results confirmed that the first and third predicted patterns were consistent with attractor states (i.e., (1) glottal onset/speech quality/low Fo and (3) breathy onset/falsetto quality/high Fo) based on 94% correct production for triad (1) and 90% correct production for triad (3) (Steinhauer, 2001). The second predicted pattern (i.e., (2) simultaneous onset/mixed quality/mid Fo) was correctly produced 75% of the time and was thus not identified as an attractor state (Steinhauer, 2001).

Steinhauer's findings (2001) were the first to shed light on possible vocal attractor states in healthy adults with dynamic systems theory of motor behavior as the theoretical foundation. The identification of possible attractor states for voice, therefore, contributed an important addition to the literature, which has primarily focused on limb behavior in the dynamic systems theory approach to motor behavior. Some limitations, however, in the methodology of Steinhauer's (2001) methodology raise some questions. Subjects had access to auditory feedback of their voice productions during the experiment. In addition, the experimenter also demonstrated the target voice production before each trial. The presence of auditory feedback with vocal modeling by the experimenter arguably provided support for learning, enabling subjects' cognitive resources to interact with the tissue and muscle coordinative dynamics of the voice production system. According to Kelso (1995) and Wallace (1996), stable motor patterns have been identified without the involvement of sensory feedback and modeling of correct productions. In other words, the subject does not need the subordinate function of sensory feedback to produce a synergistic attractor state if it exists within that coordinative system.

From Steinhauer's results (2001), it is difficult to determine if the identified "attractor states" were influenced by the external variables of modeling and sensory feedback. Posed in terms of a question, were stable patterns truly intrinsically stable, or did external factors influence their emergence? Steinhauer's rationale for providing the correct vocal model was that it should limit "subject fatigue" during attempts to approach target voice patterns (Steinhauer, 2001). If the subject was fatigued and searching for a target, then perhaps the pattern was not an intrinsic attractor state, but was something different than that.

A second limitation in the study by Steinhauer (2001) was that the dependent variable, percent correct of acquisition trials, was determined perceptually by the experimenter during subject testing and two independent raters after data collection. Interjudge and intrajudge evaluation of the examiner's rating of correct production during data collection was performed on 20% of the total stimuli (507 tokens) by the examiner and two independent raters. The intraclass correlation coefficienct (ICC) comparing interjudge reliability for the independent raters during the listening session and the examiner during subject testing was .83. The ICC comparing intrajudge reliability of the examiner during data collection and the examiner during the listening session was .89. The interjudge and intrajudge agreement between the examiner and the two independent raters was highly correlated; however, the interjudge and intrajudge evaluation was performed on only 20% of the total stimuli. Would the agreement between the examiner and the two independent raters be highly correlated with 100% of the total stimuli used for interjudge and intrajudge evaluations? Although the agreement between the experimenter and the 2 independent raters was relatively well correlated, the dependent variable was perceptually determined. Thus, Steinhauer's results may have been confounded by the use of inherently unstable perceptual measures, and also by the potential influence of 100% knowledge of results (KR) with modeling of target behaviors in the experiment.

In summary, to assess the presence of attractor states in voice production with dynamic systems theory of motor behavior and the HKB (1985) model as a theoretical foundation, three requirements must be met that have not yet been satisfied in the literature: (1) emphasis must be placed on identifying component parts of the dynamic vocalization system that may couple or act synergistically to produce voice, (2) the coordination dynamics of a voice task must be evaluated with and without auditory feedback and (3) stable dependent variables must be identified that reflect synergistic interactions across two coordinated movement subsystems. A broader point for the present discussion is the possible generality of the HKB (1985) model of motor behavior to movement systems outside the limbs using voice production as the case in point.

In conclusion, two limitations of the dynamic systems theory of motor behavior are relevant to the present investigation: (1) limited consideration of the role of sensory feedback in classic dynamic systems models, and (2) limitations in the methodology for identifying attractor states for voice production in previous work. Accordingly, to bring the dynamic systems approach closer to the training arena in both physical and voice therapy, future investigations should focus on (1) exploring the role of visual feedback and auditory feedback in the coordination dynamics of a limb and voice task, and (2) identifying attractor states in voice production with sound methodology that does not depend on unstable perceptual judgments. The relevance of this work for theory has to do with expanded understanding of interactions between the synergistic moving system and sensory feedback in motor control with the goal of gaining increased descriptions of human motor behavior outside the limb system. The relevance of this work for a specific practice arena has to do with the sensory feedback component of the candidate's developing *Global Voice Therapy Program*, which includes auditory and kinesthetic recognition of "old" voice behaviors versus "new" voice behaviors in vocal rehabilitation.

1.3 GAPS IN THE LITERATURE ADDRESSED IN THE PRESENT STUDIES

As previously noted at the outset of this chapter, schema theory is an approach to motor control and learning that emphasizes top-down command functions in control and learning. Although a role of sensory feedback is suggested in schema theory, a central feature in schema theory has to with a hypothetical, generalized motor program that regulates movement. Recent views of nervous systems organization and function (Crick & Koch, 1990, 2003; Guillery & Sherman, 2002; Hsiao et al., 1993; Jones, 2001; Niebur et al., 2002) suggest the need for a view of motor control and learning that incorporates a dynamic heterarchy of operations. From a neurophysiological perspective, dynamic systems theory's strength can be seen in its emphasis on emergent system interactions. Although recent adaptations of dynamic systems theory and the HKB (1985) model consider external sensory influences in motor control and learning, they are underemphasized and heterarchical influences are underrepresented (Schöner & Kelso, 1988a, 1988b; Peper et al., 2000).

Specifically, in dynamic systems theory, intrinsic dynamics or the stability properties of a potential attractor landscape are inherent to the system with no need for external variables to influence the patterns of behavior that emerge (Kelso, 1995; Wallace, 1996). Such external variables may include the influences of attention, perception, and visual and auditory feedback. In fact, recent evidence suggests that the stability of a 0° in-phase pattern in bimanual coordination may be more related to perceptual factors rather than motoric movement goals (Mechsner et al., 2001, 2004). In addition, recent evidence also exists for the role of attention (Monno et al., 2000; Temprado et al., 2002; Temprado et al., 1999; Zanone et al., 2001; Zanone et al., 1999) and feedback (Cardoso de Oliveira & Barthelemy, 2005; Kazennikov et al., 2002; Serrien & Teasdale, 1996; Swinnen et al., 2000) on the coordination dynamics of bimanual tasks. To address this gap, further research meeting the requirements of the original HKB (1985) model is warranted to investigate the nature and existence of coordination dynamics for a limb and a voice task with and without sensory feedback.

More broadly, greater advances are needed in the understanding of how sensory feedback and motor mechanisms interact in adaptive, biological systems. Such advances are important for theoretical reasons, as outlined, and they are also important for more pragmatic reasons related to the development of physical training and rehabilitation programs that emphasize a heterarchical perspective. Specifically, (1) information is needed about the effects of sensory feedback on the coordination dynamics and stability properties of a dynamic, moving system; and (2) information is needed about the generalization of findings across limb and other motor tasks. The present studies addressed these gaps by assessing the effect of sensory feedback on coordination dynamics for performance of an upper limb and a voice task.

1.4 FURTHER EXTENSION OF DYNAMIC SYSTEMS THEORY PERSPECTIVE TO THE CASE OF VOICE PRODUCTION

To extend the investigation of coordination dynamics beyond the typical limb task to a voice task, an order parameter (i.e., the index along which coordinative patterns emerge) of the dynamic voice production system was identified. The respiratory and laryngeal subsystems must coordinate to maintain a constant subglottic pressure, a constant airflow, and a relatively constant upper airway constriction for production of a steady state utterance, sustained vowel, and repetition of a single syllable (Hixon, 1973). These physiological requirements for production of steady-state utterances, sustained vowels, and repetitions of single syllables are accomplished by interactions among hard tissues, soft tissues, and aerodynamic factors across the respiratory and laryngeal subsystems. A combined measurement variable that captures relations among respiratory and laryngeal functions, therefore, would reflect one aspect of the coordinative nature of voice production. Laryngeal resistance (i.e., subglottic pressure divided by average airflow, Smithern & Hixon, 1981) representing the respiratory and laryngeal subsystems by subglottic pressure (cmH2O) and average airflow (l/s), respectively, is such a measure that could be classified as an order parameter of the dynamic voice production system.

According to Bernstein's (1967) degrees of freedom hypothesis, independent moving systems synergistically couple for the production of functional gestures. Within this framework for a bimanual coordination task, relative phase has 2 degrees of freedom; one for the right limb and the other for the left limb. Relative phase reflects the synergistic coupling of the 2 upper limbs. Similarly for a voice coordination task, laryngeal resistance has two degrees of freedom; one for the respiratory subsystem (i.e., subglottic pressure) and the other for the laryngeal subsystem (i.e., average airflow). The respiratory and laryngeal subsystems function independently from one another for basic life functions, such as, breathing and swallowing; however, the two subsystems couple to act synergistically in speech and voice production. In the following section, the component measurement variables of laryngeal resistance will be discussed relative to their ability to reflect changes in the respiratory and laryngeal subsystems of voice production.

1.4.1 Subglottic Pressure

To better understand subglottal pressure as a reflection of muscular force changes within the respiratory system during voice production, a brief explanation of the mechanical events for quiet breathing is relevant. At initiation of inhalation, the dimensions of the chest wall are increased by thoracic muscle contraction and possibly lowering of the diaphragm. The lungs are attached to the chest wall by pleural linkage (Kent, 1997; Zemlin, 1998). As the dimensions of the chest wall are increased, the lungs are also expanded. This increase in lung volume creates a negative pressure relative to atmospheric, causing air to flow from the atmosphere into the lungs until atmospheric and alveolar pressure with the lungs are equalized (Kent, 1997; Zemlin, 1998). At this point, the muscles of inhalation cease to contract, and the thorax-lung complex rebounds slightly to create a positive pressure within the lungs, relative to atmospheric (Kent, 1997; Zemlin, 1998). Once positive pressure is achieved within the lungs, the air is then exhaled. In quiet, resting breathy, the expiratory phase occurs by passive forces alone rather than by any active, muscular forces. Simply stated, quiet breathing requires muscle contraction for the inspiratory phase, whereas the expiratory phase may be passive or nonmuscular (Kent, 1997; Zemlin, 1998). Pressures that are generated by passive or nonmuscular forces of respiration are called relaxation pressures (Hixon, 1973).

With the discussion of quiet breathing, it is assumed that the vocal tract is neutral and the vocal folds are abducted creating no additional resistance to airflow. During voice production of a steady state utterance, however, the vocal folds and the vocal tract introduce a resistance to the flow of air. The respiratory system handles this additional resistance to the flow of air by regulating muscular and nonmuscular forces to achieve the desired subglottal pressure (Kent, 1997; Hixon, 1973). Subglottal pressure (i.e., cmH2O) is the measurement of pressure within the lungs at any given lung volume (Kent, 1997; Zemlin, 1998). During the production of steady state utterances, constant pressures are achieved by a combination of active muscular and passive recoil forces. Somewhat paradoxically, muscular actions during speech exhalation may be expiratory, inspiratory, or both, depending on the task. For example, a steady state utterance of normal loudness (e.g., 7 cmH2O), produced at high lung volumes between 100-70% Vital Capacity, will activate inspiratory muscle force at the outset of the utterance to oppose the excessive positive relaxation pressures for exhalation (Hixon, 1973; Kent, 1997). This inspiratory muscle effort in such circumstances is referred to as "checking action" against the spring-like background force of excessive relaxation pressures (Hixon, 1973; Kent, 1997). In contrast to high lung volumes, intermediate lung volumes of 60-35% Vital Capacity necessary for conversational speech at a normal loudness will activate expiratory and inspiratory muscular force to meet the demands of the utterance at 7 cmH2O (Hixon & Weismer, 1995).

The amount of inspiratory and expiratory muscle effort will vary depending upon the subglottal pressure demands for a particular utterance at a given lung volume. For example, a loud utterance produced at 55% Vital Capacity with a high subglottal pressure of 20 cmH2O will have increased expiratory and inspiratory muscular activity to counteract relaxation pressure (Hixon & Weismer, 1995). In contrast, a quiet utterance produced at 55% Vital Capacity with a lower subglottal pressure of 5 cmH2O will require less activation of expiratory and inspiratory muscular force to counteract relaxation pressure (Hixon & Weismer, 1995). The respiratory pump, therefore, achieves the demands of voice production by supplying the required inspiratory and expiratory muscular force to achieve the desired subglottal pressure (Hixon, 1973; Hixon & Weismer, 1995; Kent, 1997). The important implication is that each subglottal pressure produced in voice production demands a different inspiratory and expiratory muscular *force* at any given lung volume.

1.4.2 Average Airflow

The other measurement variable of interest in the present context is average airflow through the glottis (i.e., liters/second). During voice production, airflow from the lungs is modulated at the larynx and specifically, by the vocal folds. The contraction of the posterior cricoarytenoid (PCA) muscle abducts the vocal folds, lowering resistance to the flow of air, whereas contraction of the thyroarytenoid (TA) and other vocal fold adductors narrows the glottic opening and raises the resistance to the flow (Stevens, 1981). Resistance to the flow of air changes by modulating glottal closure; therefore, the average airflow through the vocal folds will vary.

For phonation, the vocal folds are adducted and at a certain point, when subglottic pressure exceeds the pressure of closure, a combination of aerodynamic and myoelastic factors cause the vocal fold mucosa to vibrate passively. The mucosa opens and closes in rapid succession (e.g., about 100 times per second in typical adult male phonation and about twice that rate in typical adult female phonation). An average amount of airflow through the glottis can be calculated, that reflects the amount of persistent glottal gap across the cycle (Alku & Vilkman, 1996; Stevens, 1981). Thus, average glottal airflow typically varies across different glottal configurations such as those involving (1) spread arytenoid cartilages or relative vocal fold abduction, (2) intermediate cartilage positioning, and (3) constricted glottis or "pressed" vocal folds (Alku & Vilkman, 1996; Stevens, 1981). Those three glottal configurations essentially define “boundary” configurations and tend to correspond perceptually to (1) breathy voice, (2) normal voice, and (3) pressed voice, respectively (Alku & Vilkman, 1996; Stevens, 1981). Breathy voice is produced with the vocal folds partially abducted, usually in the region of the arytenoid cartilages (Alku & Vilkman, 1996; Stevens, 1981). Decreased laryngeal resistance due to the separated arytenoid cartilages or relative vocal fold abduction in breathy voice allows for increased average airflow. In contrast, pressed voice is produced by forcing the vocal folds together, so that during a cycle of vibration the glottis opens only along a portion of the vocal fold length (Alku & Vilkman, 1996; Stevens, 1981). Increased laryngeal resistance due to the constricted glottal configuration allows for decreased average airflow.

In summary, the laryngeal system functions as a variable resistor to the flow of air from the respiratory system. The degree of resistance produced by the vocal folds to the flow of air is regulated by adduction and abduction force changes in the muscles and tissues of the larynx. Measurement of average airflow, therefore, is an indirect measure of the degree of resistance and specifically, the muscle and tissue force changes of the vocal folds during different glottal configurations. Subglottal pressure and average airflow have been demonstrated to estimate tissue and muscular force changes across the respiratory and laryngeal systems, respectively. Laryngeal resistance (i.e., subglottic pressure divided by average airflow, Smitheran & Hixon, 1981), therefore, is an order parameter (i.e., the index along which coordinative patterns emerge) of the dynamic voice production system that reflects the coordination among the respiratory and laryngeal subsystems with two degrees of freedom. Within a given individual during a given measurement session, a steady-state phonation with unchanging fundamental frequency, intensity, and vowel quality should reflect constant force *relations* across the sum of passive and active respiratory forces, and the sum of passive and active laryngeal forces contributing to adduction (Smitheran & Hixon, 1981). The next sections provide information about data relative to laryngeal resistance in phonation.

1.4.3 Normative Studies Involving Laryngeal Resistance

The basic paradigm for the collection of laryngeal resistance was established by Smitheran and Hixon (1981). Prerequisite to the calculation of laryngeal resistance is a methodology for non-invasively estimating both subglottic pressures and glottal flows during phonation. A landmark study was published in that regard by Smitheran and Hixon (1981). A key issue in their work was the ability to estimate phonatory subglottic pressures non-invasively from oral pressures during strings of repeated /pi/ utterances. Estimates of subglottal pressure were taken from the peaks of intraoral pressure recorded during the voiceless portion of the bilabial consonant /p/. During the /p/ sound, the lips and the velopharynx are closed while the vocal folds are apart. Assuming sufficient time during the occlusion phase, the pressures throughout the vocal tract, larynx, and subglottis should equalize. Thus, pressures obtained from the oral cavity during /p/ occlusion should reflect pressures in the subglottis. The pressures throughout the vocal tract, larynx and subglottis, therefore, are uniform.

Fifteen adult males produced the utterance /pi/ at a repetition rate of 1.5 syllables/sec (i.e., 92 beats per minute). Subjects were asked to take a breath before the utterance and to produce the utterance on a single, continuous expiration at a normal loudness and pitch level to approximate normal conversational speech. Airflow was channeled through a large, hard-rubber, anesthesia mask positioned over the mouth and nose. Flow from the mask was channeled through a pneumotachometer. Intraoral pressure was recorded by a small-diameter polyethylene tube passed through the face mask with the proximal end positioned in the oral cavity on top of the tongue. The resulting flow-analog and pressure-analog signals were monitored and recorded on an oscilloscope. The mean laryngeal resistance for the 15 male subjects was 35.7 $cmH_2O/l/sec$ (Smitheran & Hixon, 1981).

Comparison of mean laryngeal resistance values from the non-invasive methodology (Smitheran & Hixon, 1981) to the combined weighted mean of three invasive studies which used tracheal puncture to obtain subglottic pressure for the laryngeal resistance ratio (Kunze, 1962; Sant & Logemann, 1970; Shipp & McGlone, 1971) indicated a difference of 1.5 $cmH_2O/l/s$ between the two sets of data. No statistical tests were reported to compare the two sets of data. Based on descriptive analyses, the closeness in values between the non-invasive methodology (Smitheran & Hixon, 1981) and the invasive tracheal punctures (Kunze, 1962; Sant & Logemann, 1970; Shipp & McGlone, 1971) suggested that the method presented by Smitheran and Hixon (1981) was adequate in estimating laryngeal resistance during production of the /pi/ utterance.

Once the method of noninvasive aerodynamic evaluation had been established by Smitheran and Hixon (1981), researchers in the 1980s and 1990s established normative data on pressure and airflow. The relevant investigations focused on the effects of variations in pitch and loudness on pressure and airflow (Holmberg et al., 1988, 1989; Stathopoulos & Sapienza, 1993; Tang & Stathopoulos, 1995), and the effects of age and gender on pressure and airflow (Goozee, Murdoch, Theodoros & Thompson, 1998; Stathopoulos & Weismer, 1985, Tang & Stathopoulos, 1995).

Relative to combined measures reflecting synergistic relations between pressure and airflow, other studies have also assessed another measure reflecting phonation synergies, vocal efficiency. Vocal efficiency is defined as voice output intensity divided by subglottic pressure times average airflow (Schutte, 1981). Vocal efficiency as well as laryngeal resistance increased as intensity increased (Holmberg et al., 1988; Ishiki, 1981; Schutte, 1981; Stathopoulos & Sapienza, 1993; Tang & Stathopoulos, 1995). Vocal efficiency and laryngeal resistance measures may be more directly related to vocal fold mechanisms controlling intensity rather than vocal fold mechanisms controlling pitch (Holmberg et al., 1989). In addition, vocal efficiency and subglottal pressures were lower in children than adults (Tang & Stathopouls, 1995) possibly due to the differences in laryngeal structure as a function of age. Discrepancies between average airflow and sound pressure levels (SPL) across gender and age were seen in the literature (Goozee et al., 1998; Higgins & Saxman, 1991; Ludlow, Bassich & Connor, 1985; Stathopoulos & Weismer, 1985). For example, two studies reported that males have increased average airflow rates as compared to females during consonant-vowel-consonant productions (Higgins & Saxman, 1991; Stathopoulos & Weismer, 1985), while another study reported the opposite effect (Goozee et al., 1998). Finally, Holmberg and colleagues (1994) demonstrated that laryngeal resistance and average airflow had a high degree of variability and should not be used as measures to quantify subtle changes in vocal fold function related to intensity level.

1.4.4 The Capability of Laryngeal Resistance to Distinguish Pathological from Normal Voice Production

In addition to normative studies on variations of loudness and pitch and age and gender effects on pressure and airflow, researchers have also investigated the capabilities of pressure and airflow to distinguish pathological from normal voice production and some pathological conditions from one another (Grillo & Verdolini, in preparation; Hillman, Holmberg, Perkell, Walsh & Vaughan, 1989, 1990; Laukkanen, Lindholm & Vilkman, 1995; Netsell, Lotz & Shaughnessy, 1984; Rammage, Peppard & Bless, 1992).

Hillman and colleagues (1989) established a theoretical framework for vocal hyperfunction. Vocal hyperfunction was divided into two groups; adducted hyperfunction and nonadducted hyperfunction. Adducted hyperfunction included organic lesions (e.g., nodules, polyps, and contact ulcers), while nonadducted hyperfunction included nonorganic conditions (e.g., Muscle Tension Dysphonia or Muscle Tension Aphonia). Data collection of pressure and airflow were similar to the normative study discussed previously (see, Smitheran & Hixon, 1981). Fifteen subjects with visual-perceptual diagnosis of adducted hyperfunction and nonadducted hyperfunction produced 5 productions of the /pae/ syllable at a rate of 1.5 syllables/second. Subjects were asked to produce this syllable string using each of the following kinds of voice: 1) normal pitch and loudness, 2) softer than normal, 3) louder than normal, 4) lower pitched than normal, and 5) higher pitched than normal. Results indicated that neither the ratios of laryngeal resistance nor vocal efficiency detected voice dysfunction relative to norms in either of the patient groups. The authors attributed this finding to the large variability in the average flow rates and the elevated values of subglottic pressure, which made the ratios involving these parameters (i.e., laryngeal resistance and vocal efficiency) fall within the normal range. Hillman and colleagues (1989), therefore, questioned the utility of these ratios for clinical evaluation purposes. In a study a year later, Hillman and colleagues (1990), elected not to report laryngeal resistance and vocal efficiency due to the ratios' insensitivity in detecting phonatory hyperfunction (Hillman et al., 1989).

Using the noninvasive technique to acquire subglottic pressure estimates and average airflow as described in Smitheran and Hixon (1981), Netsell and colleagues (1984) attempted to correlate laryngeal resistance values to voice quality. Eighteen subjects with a diagnosed voice disorder provided a speaking voice sample for expert rating and participated in the aerodynamic assessment similar to the methods described in Smitheran and Hixon (1981). The content of the speaking voice sample was not specified. Three experienced speech-language pathologists rated each sample on a scale from 0-7 with 0 representing normal limits and 7 representing severe deviation for each dimension of breathy, rough, and strained. The following definitions were used for the 3 voice qualities: 1) breathy, perception of excessive laryngeal airflow; 2) rough, perception of aperiodic perturbations in frequency, intensity, or both; and 3) strained, perception of hyperadduction in the laryngeal airway, excessive subglottal pressure or both (Netsell et al., 1984). Intralistener agreement was 47% for exact scaler agreement, while the interlistener agreement was generally within one scale point of each other.

Several trends were evident from the foregoing data (Netsell et al., 1984). When pressure was normal and flow exceeded 400 ml/sec, patients' voices were perceived as breathy. The combination of low flow and excessive pressure, or pressures greater than 10 cmH2O, resulted in the perception of a strained voice. Combinations of high flows and high pressures generally resulted in the perception of a rough voice. No statistical analysis was completed to determine if the laryngeal resistance values were significantly different from one another and if the voice quality ratings accurately predicted the laryngeal resistance values. The results of the study are purely descriptive in nature. The data, however, provided a valuable antecedent to later work that attempted to address relations between voice quality and measures of functional synergies in phonation.

In fact, the voice qualities of pressed, normal, resonant, and breathy were used in two studies that attempted to distinguish their distinct adduction patterns by acoustic and highbandwidth aerodynamic measures, visual inspection, and electroglottography (EGG), but not by relational measures (Alku & Vilkman, 1996; Peterson, Verdolini-Marston, Barkmeier & Hoffman, 1994). The four voice qualities of pressed, normal, resonant, and breathy were defined by their equivalent vocal fold adduction patterns: (1) constricted glottis, (2) neutral glottis, (3) slightly more abducted or adducted than neutral glottis, and (4) separated arytenoid cartilages or relative vocal fold abduction, respectively (Verdolini et al., 1998; Stevens, 1981).

In the first study, Alku and Vilkman (1996) described breathy and pressed voice as the extreme vocal fold closure patterns to normal closure patterns. In the study by Alku and Vilkman (1996), breathy, pressed, and normal voice qualities were used to find a quantification technique that most clearly distinguished the three voice types. Five female and 5 male subjects were asked to sustain /a/ for two seconds at a comfortable pitch and loudness level across all three voice qualities. Quantification techniques of the voice source involved: three time-based quotients extracted from the glottal flow waveforms, two time-based parameters that were extracted from the flow and its first derivative, one amplitude-based parameter that was defined as both the flow and its first derivative, and one frequency-domain parameter that was computed from the flow signal. The results indicated that the voice qualities were distinguished from each other most effectively by using the parameters that were extracted from the instant of maximum glottal opening to the minimum peak of the flow derivative as well as the frequency-domain parameterization.

In the second study, Peterson and colleagues (1994) used breathy, pressed, normal, and resonant voice qualities to determine the most effective measurement tool in distinguishing the four critical voice productions. The measurement tools included: 1) aerodynamic measures; minimum flow, alternating current (AC flow), and maximum flow declaration rate (MFDR), 2) electroglottography (EGG), and 3) videostroboscopic images. Minimum flow is the amount of airflow through the glottis when the vocal folds are at their maximum closure (Holmberg et al., 1988, 1989). AC flow is the amount of airflow modulated by vocal fold vibration and MFDR is the greatest rate at which airflow is decelerated during vocal fold closure (Holmberg et al., 1988, 1989).

The closed quotient from the EGG signal of vowels /a/ and /i/ distinguished the four voice qualities from one another (Peterson et al., 1994). The videostroboscopic images distinguished pressed voice from the other voice types in terms of laryngeal adduction ratings. Aerodynamic measures of minimum flow, AC flow, and MFDR yielded differences between the voice qualities, but nothing significant. Both Alku and Vilkman (1996) and Peterson and colleagues (1994) were successful in distinguishing the voice types. Alku and Vilkman (1996) distinguished the voice types by using the glottal flow waveform and the frequency-domain parameterization, while Peterson and colleagues (1994) distinguished the voice types by EGG and videostroboscopic images.

The literature clearly indicates that the four voice qualities have been discussed and even tested for distinguishing characteristics; however, the distinguishing characteristics did not involve relational measures between the sub-systems of the voice production system. Grillo and Verdolini (in preparation) tested whether or not four different adduction patterns of the vocal folds were distinguishable from one another by relational measures of laryngeal resistance and/or vocal efficiency. Laryngeal resistance and vocal efficiency are two aerodynamic and acoustic dependent variables that reflect muscular and tissue force measurement of the laryngeal system and the respiratory drive necessary for voice production.

In the study by Grillo and Verdolini (in preparation), 13 trained voice professionals produced 5 sequential /pi/s across three trials at a production rate of 88 beats per minute in a normal, resonant, pressed, and breathy voice quality (Grillo & Verdolini, in preparation). Perceptual procedures were used to verify voice quality for each utterance. Fundamental frequency was held constant at 220 Hz and intensity level was produced at a comfortable average (+/- 1 dB) based on each subjects' conversational speech. After a brief training phase, subjects produced the target utterance for each voice quality into a Rothenberg (1973) circumferentially vented pneumotachograph face mask attached to the Aerophone II software program. A pressure transducer was attached to the mask at one end and the other end was placed in the subject's mouth between the lips on top of the tongue. Custom software was used to compute average airflow, average dB, and average intraoral pressure for each trial, where pressures were computed using methodology described by Holmberg and colleagues (1988). Laryngeal resistance and vocal efficiency were then calculated (i.e., laryngeal resistance = average subglottic pressure divided by average airflow, Smitheran & Hixon, 1981; vocal efficiency = average dB divided by average subglottic pressure times average airflow, Schutte, 1981).

Results showed that laryngeal resistance distinguished all the voice qualities from one another except normal and resonant, while vocal efficiency only distinguished breathy from normal, resonant, and pressed (Grillo & Verdolini, in preparation; see Tables 1-3). The point for the present discussion is that laryngeal resistance – but not vocal efficiency – was shown to be a useful measure to capture synergistic relations across respiratory and laryngeal subsystems of phonation, failing to distinguish only normal and resonant voice. It is likely that the difference between normal and resonant voice qualities does not reside with differences in respiratory-laryngeal relations, but rather with changes in the vocal tract.

Laryngeal Resistance	Significance	95% CI
R=N	.347	-24.23, 4.87
R≠ B	.000 *	11.06, 29.86
R≠ P	.004 *	-729.78, -133.29
N≠ B	.000 *	18.32, 41.96
N≠ P	.004 *	-714.78, -128.93
B≠ P	.003 *	-748.47, -155.52

Table 1. Laryngeal resistance (cm H2O/l/s) pairwise comparisons for R=Resonant, N=Normal, P=Pressed, and B=Breathy with 95% confidence intervals. (Asterisk indicates a significant difference for the pairwise comparisons, *p*= .05).

Vocal Efficiency	Significance	95% CI
R=N	1.0	-31.23, 32.96
R≠ B	.000 *	38.51, 101.38
R=P	.108	-236.19, 16.65
N≠ B	.000 *	-88.78, -49.37
N=P	.152	-247.29, 26.00
B≠ P	.006 *	-311.26, -48.17

Table 2. Vocal efficiency (dB/cmH2O/ l/s) pairwise comparisons for R=Resonant, N=Normal, P=Pressed, and B=Breathy with 95% confidence intervals. (Asterisk indicates a significant difference for pairwise comparisons, *p*= .05).

	Sample Mean	95% Confidence Intervals
Laryngeal Resistance, breathy	11.84	10.35, 13.33
Laryngeal Resistance, normal	41.98	33.04, 50.93
Laryngeal Resistance, pressed	463.83	258.31, 669.35

Table 3. Sample mean and 95% confidence intervals that could cover the population parameter of μ for breathy, normal, and pressed voice qualities by laryngeal resistance (cm H2O/l/s).

In summary, Hillman and colleagues (1989, 1990) found that laryngeal resistance and vocal efficiency were unable to distinguish voice hyperfunction from normal voice. Netsell and colleagues (1984) descriptively correlated laryngeal resistance to voice quality. Even though Netsell and colleagues (1984) did not statistically test for a direct correlation between laryngeal resistance and voice quality, a rationale based on descriptive trends in the data was established for future direct tests. Grillo and Verdolini (in preparation) provided direct evidence that laryngeal resistance distinguished the pairwise combinations of pressed, normal, resonant, and breathy voice qualities, except normal and resonant voice, which are likely distinguished by vocal tract characteristics. Based on those data, laryngeal resistance is a valid measure that reflects an order parameter of the dynamic voice production system and specifically, a functional synergy across respiratory and laryngeal subsystems.

1.5 STATEMENT OF PURPOSE, SPECIFIC AIMS, EXPERIMENTAL QUESTIONS, AND HYPOTHESES

The general goal of the proposed studies was to address theoretical issues exploring the intersection of sensory feedback and coordinative dynamics in an emerging theoretical framework that emphasizes heterarchical influences in motor control. A bimanual coordination task was selected for study because (a) the task was associated with a well-established experimental paradigm, and thus results from the present series can be compared and verified against findings from previous work; (b) the task established the validity of the experimental design; and (c) the task involved upper limb coordination, which is ultimately relevant for a wide range of occupational and physical therapy targets. Examples include upper limb mobility exercises for individuals with decreased limb function (Mulder, 1991; Mulder et al., 2004; Steenbergen et al., 2000) and functional exercises relevant to repetitive motions such as assembly line factory work and piano playing (Haslinger, Erhard, Altenmuller, Hennenlotter, Schwaiger, von Einsiedel, Rummeny, Conrad & Ceballos-Bauman, 2004; Parlitz, Peschel & Altenmuller, 2004; Ragert, Schmidt, Altenmuller & Dinse, 2004).

A voice task was selected for study because (a) the task represented a functional gesture based on communication rather than movement; (b) the task required expertise in manipulating the voice production system; (c) the task represented an actual training activity that is directly relevant to behavioral therapy for a broad range of conditions affecting voice (Berry, Verdolini, Montequin, Hess, Chan, & Titze, 2001; Grillo & Verdolini, in preparation); (d) the sensory feedback condition was a relevant component of the candidate's developing *Global Voice Therapy Program*; and (e) the task extended the inquiry of motor control beyond the typical bimanual coordination domain (i.e., bimanual upper limb movement) to a task that required biomechanical coupling of the respiratory and laryngeal subsystems for the production of voice. In the literature, studies involving biomechanical coupling for motor coordination were investigated in finger tapping, finger-wrist, and lower jaw-lower lip paradigms; therefore, the voice task was consistent with investigations extending beyond the typical bimanual limb movements (Liao & Jagacinski, 2000; Mechsner et al., 2001; Mechsner & Knoblich, 2004; Kelso & Bateson, 1983; Kelso & Tuller, 1984). Specific aims, rationale, experimental questions, and hypotheses are as follows:

#1) (Experiment 1):

Specific aim: To assess the influence of (i) visual and auditory sensory feedback; (ii) relative phase pattern; (iii) increasing oscillation frequency, and (iv) their interaction on motor performance for a bimanual coordination task.

Rationale: The rationale for the sensory feedback condition was to challenge coordination dynamics where sensory feedback influences are underemphasized in the performance of movement output. A second rationale for assessing the role of sensory feedback in bimanual coordination was to seek replication of previous research indicating relevance of feedback for such tasks (Cardoso de Oliveira & Barthelemy, 2005; Kazennikov et al., 2002; Serrien & Teasdale, 1996; Swinnen et al., 2000). In addition, evaluating the role of increasing frequency on relative phase was pursued to seek replication of previous research demonstrating that the 0º in-phase pattern is more stable than the 180º anti-phase pattern (Kelso, 1984; Scholz & Kelso, 1989, 1990; Tuller & Kelso, 1989).

Based on the literature, two potential attractor states of relative phase were targeted for investigation: 0° in-phase and 180° anti-phase patterns. Those relative phase patterns were produced at increasing frequencies of 1 Hz, 2 Hz, and 3 Hz, corresponding to slow, medium, and fast speeds, respectively, to assess the influence of sensory feedback as a function of task difficulty.

Experimental questions and hypotheses:

1) Will there be a significant interaction among the effects of 4 sensory feedback conditions, 2 relative phase patterns, and increasing frequency of oscillation for a bimanual coordination task?

Ho¹: There is no significant interaction among the effects of 4 sensory feedback conditions (i.e., visual + auditory feedback; visual feedback only; auditory feedback only; no visual and no auditory feedback), 2 relative phase patterns (i.e., 0º and 180º), and increasing frequency of oscillation or speed (i.e., 1Hz, 2Hz, and 3Hz) on the mean error of relative phase and/or the standard deviation of relative phase.

2) Will there be a significant interaction among the effects of 2 relative phase patterns and the increasing frequency of oscillation for a bimanual coordination task?

Ho²: There is no significant interaction among the effects of 2 relative phase patterns (i.e., 0º and 180º) and increasing frequency of oscillation or speed (i.e., 1Hz, 2Hz, and 3Hz) on the mean error of relative phase and/or the standard deviation of relative phase.

#2) (Experiment 2):

Specific aim: To assess the influence of (i) auditory sensory feedback, (ii) voice quality; (iii) increasing fundamental frequency (Fo); and (iv) their interaction on motor performance for a voice coordination task.

Rationale: The rationale for assessing the role of sensory feedback in a coordinative voice task was to explore the generality of results from the limb study. Consistent results across limb and voice tasks would speak to general principles of motor control rather than domain-specific principles, and would thus contribute to general models of motor control. The dependent variable was laryngeal resistance (cmH2O/l/s), which has been shown to reflect functional synergies across respiratory and laryngeal subsystems in voice production (Grillo & Verdolini, in preparation). Specifically, three potential attractor states for laryngeal resistance were identified for study that previous research has shown to generally correspond to breathy voice quality (i.e., 10.35-13.33 cmH20/l/s), pressed voice (i.e., 258.31-669.35 cmH20/l/s), and normal voice (i.e., 33.04-50.93 cmH20/l/s). Each target voice quality was produced at a series of fundamental frequencies ranging from 220 Hz to 880 Hz in major third increments (i.e., 220Hz, 277Hz, 349Hz, 440Hz, 554Hz, 698Hz, and 880Hz). Increasing fundamental frequency or pitch is related to the speed of vocal fold vibration located in the laryngeal subsystem and not in the respiratory system; however; biomechanical coupling between the respiratory and laryngeal subsystems helps to achieve the increase in pitch. To make the limb study and the voice study consistent across the two tasks, the increasing fundamental frequency component was determined to be as close as possible to the increasing frequency of oscillation component in the limb study. Thus, fundamental frequency changes were incorporated in the present experiment as a way of influencing task difficulty.

Experimental questions and hypotheses:

1) Will there be a significant interaction among the effects of 2 sensory feedback conditions, 3 voice qualities, and increasing fundamental frequency or pitch for a voice coordination task?

Ho^1: There is no significant interaction among the effects of 2 sensory feedback conditions (i.e., normal auditory feedback and masked auditory feedback by speech noise), 3 voice qualities (i.e., breathy, normal, and pressed), and increasing fundamental frequency or pitch (i.e., 220Hz, 277Hz, 349Hz, 440Hz, 554Hz, 698Hz, and 880Hz) on the mean of laryngeal resistance and/or the standard deviation of laryngeal resistance.

2) Will there be a significant interaction among the effects of 2 sensory feedback conditions and 3 voice qualities for a voice coordination task?

Ho^2: There is no significant interaction among the effects of 2 sensory feedback conditions (i.e., normal auditory feedback and masked auditory feedback by speech noise) and 3 voice qualities (i.e., breathy, normal, and pressed) on the mean if laryngeal resistance and/or the standard deviation of laryngeal resistance.

2.0 CHAPTER 2: EXPERIMENT 1

2.1 RESEARCH METHODS

2.1.1 Purpose

The purpose of Experiment 1 was to assess the influence of (i) visual and auditory sensory feedback (i.e., (a) visual + auditory feedback, (b) visual feedback only, (c) auditory feedback only, and (d) no visual and no auditory feedback); (ii) bimanual coordination pattern (i.e., 0° and 180° relative phase patterns); (iii) increasing frequency of oscillation or speed (i.e., 1Hz, 2Hz, and 3 Hz), and (iv) their interactions on motor performance for a bimanual coordination task.

2.1.2 Participants

Participants were 15 females, ages 18-35 years with a mean age of 21 years. Sample size was derived from prior work indicating that this subject number is sufficient to detect group differences in stability across bimanual coordination tasks (Hodges & Lee, 1999; Lee, Almeida & Chua, 2002; Mechsner et al., 2001; Serrien & Teasdale, 1996). The study was limited to females due to the emphasis on females in Experiment 2 for clinical reasons (see description of Experiment 2). Thus, for purposes of comparing results across studies, gender was kept constant throughout the series. Participants were recruited among undergraduate and graduate students at

Wilfrid Laurier University, using flyers, following approved Institutional Review Board (IRB) procedures at Wilfrid Laurier University and the University of Pittsburgh. Inclusion criteria included self-report of normal vision with or without correction by glasses or contacts and self-report of normal audition. Self-report of hand dominance of the subjects was also recorded. Twelve out of the 15 subjects were right hand dominant, while 3 out of the 15 subjects were left hand dominant.

2.1.3 Equipment and Software

The bimanual coordination apparatus involved two plastic handles (i.e., 12.5 cm in height x 3 cm diameter) independently attached to linear sliding devices that glided horizontally over ball bearings encapsulated in metal casings (see Figure 4). Limb movements were permitted in only the left-right orientation from midline. Visual markers dictated the amplitude of movements (i.e., 32cm for a complete in-out-in cycle of limb displacement). Attached in parallel to the slides were linear potentiometers (Duncan Electronics, DEL Elec 612R12KL.08), which encoded the displacement of the slides over a 20-se trial. Data were sampled using a microprocessor (80486) with a sampling rate of 200 Hz (i.e., one sample each 5 msec). LabWindows software (National Instruments Corporation, version 2.2.1) initiated and terminated 20-sec trials and also provided data capture and recording of limb position over time.

Data were stored on a Pentium 3 computer dedicated to bimanual coordination studies. An auditory metronome (NCH Swift Sound Tone Generator, version 2.01) provided pacing information for the bimanual tasks. In addition, for visual deprivation conditions, lights were extinguished and computer monitors were covered to achieve total darkness in the room, so that subjects' view of their arms was completely obstructed. In auditory deprivation conditions, a white-noise masking stimulus (NCH Swift Sound Tone Generator, version 2.01) was delivered to the subject's ears via supra-aural headphones (Optimum Pro-155 stereo headphones) so that auditory feedback about performance from the linear slides was blocked. The intensity of masking was determined individually for each subject, so that complete masking of the linear slide sounds was blocked, but intensity of masking was within comfortable limits and the metronome signal could still be perceived.

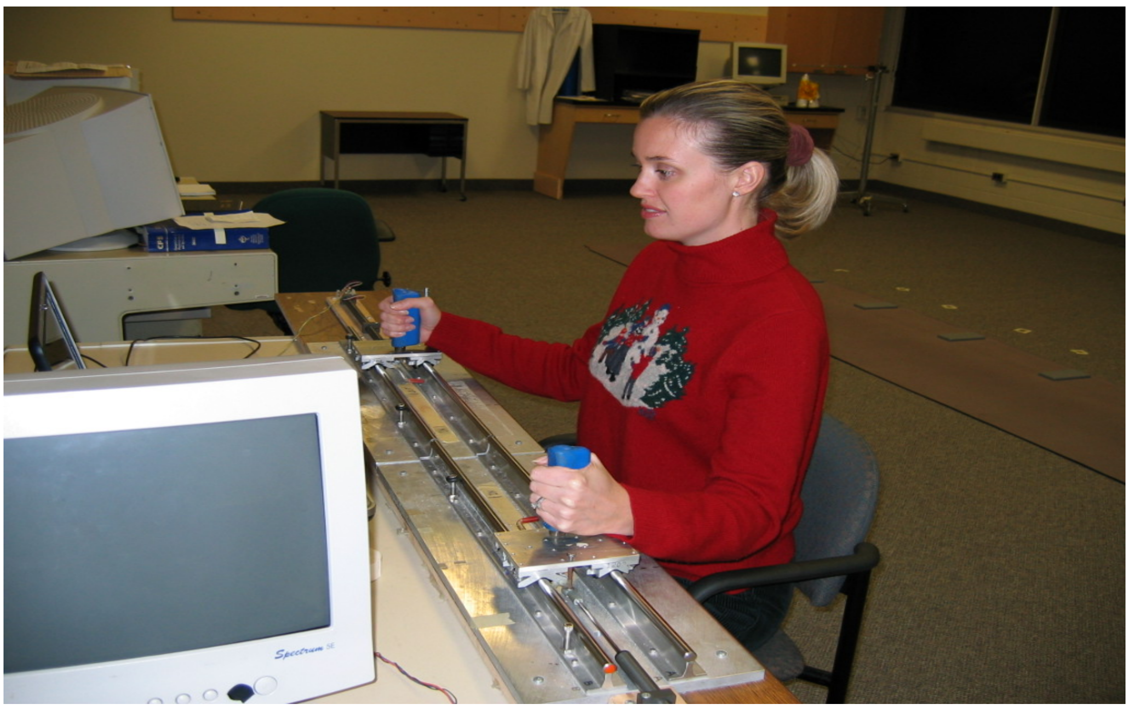

Figure 4: Bimanual Linear Slide.

2.1.4 Experimental Design

The experiment used a three-way, within-subjects repeated measures design. The three independent variables were: (1) relative phase patterns for a bimanual coordination task (i.e., 0º and 180º), (2) frequency of arm oscillation or speed (i.e., 1 Hz, 2 Hz, and 3 Hz), and (3) sensory feedback conditions (i.e., visual and auditory feedback, visual feedback only, auditory feedback only, and no visual and no auditory feedback). The dependent variables were mean error of relative phase and standard deviation of relative phase. For experimental trials, order of relative phase patterns and feedback conditions were randomly determined within and across subjects (see Table 4).

Subject Number	Sensory Feedback	Relative Phase
1	4123	21
2	3241	12
3	1243	21
4	4123	21
5	4321	12
6	4213	21
7	3241	12
8	1432	12
9	4321	21
10	2314	21
11	2413	21
12	2134	21
13	3142	12
14	2431	12
15	3412	21

Table 4. Order of the sensory feedback conditions and relative phase patterns for 15 subjects. For sensory feedback, 1= visual and auditory feedback, 2= visual feedback only, 3= auditory feedback only, and 4= no visual and no auditory feedback. For relative phase, 1= 0^{o} in-phase pattern and 2= 180^{o} anti-phase pattern.

2.1.5 Procedures

Subjects were seated in front of the bimanual coordination apparatus for all procedures. First, subjects read and signed the informed consent form, which was approved by the University of Pittsburgh's IRB and Wilfrid Laurier University's Ethics Board. Second, subjects answered questions to meet the recruitment criteria of female gender, ages 18-35 years, self-report of normal vision with or without correction by glasses or contacts, and self-report of normal audition. Self-report of hand dominance was also recorded. Third, subjects received a general orientation to the task. The task required them to grasp two handles attached to moving slides and displace them horizontally in the left-right dimension. In the 0º in-phase pattern, the limbs moved toward each other and then away from each other continuously with the same homologous muscle groups contracting at the same time (Kelso, 1981, 1984). In the 180º anti-phase pattern, the limbs moved together in a parallel fashion with the homologous muscle groups contracting in an alternating fashion (Kelso, 1981, 1984).

Subjects received instructions to keep pace with a metronome by performing a complete cycle of in-out-in handle displacement in time with the beat and to keep the moving slides within the visual markers. The metronome paced the required speed or frequency of limb movement beginning at a slow speed equivalent to a frequency of 1 Hz for 20-seconds. After completion of the 20-second trial at 1 Hz, the same required coordination task was repeated at a medium speed equivalent to a frequency of 2 Hz and subsequently a fast speed equivalent to a frequency of 3 Hz as paced by the metronome. A brief 5-second pause occurred between each speed. Each paced trial lasted for 20-seconds.

Subjects were also encouraged to maintain the required coordination pattern as best as possible throughout all trials. If the pattern destabilized, subjects were instructed to attempt a recapture of the required coordination pattern even mid-trial. Then, after verbal descriptions and demonstrations, subjects produced the 0º and the 180º relative phase patterns under a variety of feedback conditions (i.e., normal visual and auditory feedback, visual feedback only, auditory feedback only, and no visual and no auditory feedback of the arms at each of the 3 pacing frequencies (i.e., 1 Hz, 2 Hz, and 3 Hz). All 3 frequencies or speeds for one relative phase pattern were completed before switching to a new relative phase pattern, in a blocked design. In addition, subjects repeated each speed 3 times to increase the sample of data points so there was less chance of outlier performance. Order of the relative phase patterns and sensory feedback conditions were randomized within and across subjects (see Table 4).

For the normal feedback condition, subjects had a clear view of their arms and hands during the production of the relative phase patterns, and they could hear noises from the linear slides as they were displaced. As noted, in the no visual feedback condition, total visual deprivation was achieved by extinguishing all lights and covering the computer monitors so that visual access to the limbs was completely blocked. In the auditory deprivation condition, subjects received white noise presented to their ears via supra-aural headphones at an intensity level that was adequate to mask the sound produced by the bimanual slides without causing discomfort to the subject, as determined individually for subjects during the orientation phase of the experiment. Auditory pacing from the metronome, however, could be perceived above the white noise through the headphones. During the experiment, subjects received no feedback about their performance from the computer or otherwise, because such feedback might have influenced learning for the task and the focus of the present study was motor control, not motor learning.

2.1.6 Data Reduction

The dependent variables for Experiment 1 were mean error of relative phase and standard deviation of relative phase as a function of bimanual coordination task (i.e., 0º and 180°), at 3 increasing frequencies under 4 sensory feedback conditions. Data collection involved a continuous estimate methodology (Hodges & Lee, 1999), in which limb position was sampled at a rate of 200 Hz (every 5 ms). This method allowed for finer-grained information about movement accuracy as compared with point estimates, which typically focus on two time-points per cycle (Scholz & Kelso, 1990). Relative phase difference for each time point was determined in the following way. For each time point sampled, the relative phase of the right limb in space was captured, relative to the left limb, where a reference of 0º indicated that both limbs were at the midline position. In addition, the 3 repetitions of each speed were averaged for calculation of mean error of relative phase and standard deviation of the relative phase.

Mean error of relative phase was calculated for the 0º in-phase pattern and for the 180º anti-phase pattern. Specifically, the final mean error term for the 0º in-phase pattern was simply the mean relative phase because the mean relative phase error subtracted from 0 is equal to the mean relative phase. To compute the final error term for the 180º anti-phase pattern, the performed mean relative phase from each trial was subtracted from 180, so that values could be compared to those for the 0º trials. In addition to mean error of relative phase, also the standard deviation of the relative phase was computed for each experimental condition. Both values were used in statistical analyses.

2.1.7 Statistical Analysis

Statistical analyses were guided by the study's purpose. As noted elsewhere, the purpose of Experiment 1 was to examine how sensory feedback contributes to bimanual coordination dynamics and to replicate previous results demonstrating that the 0º in-phase pattern is more stable than the 180º anti-phase pattern at increasing speeds (Kelso, 1984; Scholz & Kelso, 1989, 1990; Tuller & Kelso, 1989).

A three-way, repeated measures analysis of variance (ANOVA) was conducted on each of the dependent variables. The dependent variables were mean error of relative phase and standard deviation of relative phase. The independent variables were sensory feedback condition (i.e., visual + auditory feedback, visual feedback only, auditory feedback only, and no visual and no auditory feedback), bimanual coordination task (i.e., 0º and 180º), and movement frequency (i.e., 1, 2, and 3 Hz). Significance level was set at $\alpha = .05$ and post hoc simple main effects were analyzed using the Bonferroni correction. The ANOVAs were used to test the following two statistical hypotheses (Ho):

1. Ho^1: There is no significant interaction among the effects of 4 sensory feedback conditions (i.e., visual + auditory feedback, visual feedback only, auditory feedback only, and no visual and no auditory feedback), 2 relative phase patterns (i.e., 0º and 180º), and increasing frequency of oscillation or speed (i.e., 1Hz, 2Hz, and 3Hz) on mean error of relative phase and/or standard deviation of relative phase.
2. Ho^2: There is no significant interaction among the effects of 2 relative phase patterns (i.e., 0º and 180º) and increasing frequency of oscillation or speed (i.e., 1Hz, 2Hz, and 3Hz) on mean error of relative phase and/or standard deviation of relative phase.

2.2 RESULTS

The following assumptions were applied to the within-subjects repeated measures design: (1) sphericity, (2) normality, and (3) independence by random order of the design. Relative to the first point, Huynh and Feldt (1970) demonstrated that the assumption of sphericity (i.e., variances of differences for all levels of the repeated measures factor are equal) is sufficient to obtain central *F*-distributions with nominal degrees of freedom. The assumption of sphericity was met for some, but not all of the within subjects effects. To correct for sphericity, the Huynh-Feldt (1970) correction was used for all tests. The normality assumption was met for some of the mean error and standard deviation values, but not all. Non-normality, however, has very little effect on the level of significance and the power of the *F*-test in the analysis of variance (ANOVA) when considering non-directional tests (Glass and Hopkins, 1996). Thus, the data were not adjusted for normality. It is more important to meet the assumption of independence within by random order of the design as its violation may seriously affect the level of significance and the power of the *F*-test (Glass and Hopkins, 1996). The assumption of independence within by random order of the design was met by the random order of the sensory feedback conditions and the relative phase patterns. Alpha was set at .05 for all analyses and adjusted appropriately for the number of post hoc comparisons.

2.2.1 Dependent Variable: Mean Error of Relative Phase

Results for mean error of relative phase are shown in Tables 5-8 and in Figures 5-7. Overall, mean error of relative phase was greater for the 180º condition than for the 0º condition, and was also greater for the 180º pattern at higher frequencies as compared to lower frequencies of limb oscillation. The performance of the 0º in-phase pattern was not influenced by the increasing frequencies. The accuracy in performance of the relative phase patterns, however, did not systematically vary with feedback condition.

The ANOVA for mean error of relative phase revealed significant main effects for *phase* [$F(1,14)=73.36$, $p<.000$] and *frequency* (indicated as "speed" in the Figure legends) [$F(1.36,19)=48.95$, $p<.000$] (see Table 5 and Figures 5 and 6). The main effect of *feedback* [$F(2.24,31.39)=1.13$, $p=.342$], however, was not significant. A significant two-way interaction was shown for *phase x speed* [$F(1.49,21)=41.69$, $p<.000$] (see Table 5 and Figure 7). The three-way interaction for *phase x speed x feedback* [$F(3.43,48)=.363$, $p=.806$] was not significant. Eta squared, an indicator of effect size, was .840 and .778 for the significant main effects of phase and speed, respectively and .749 for the significant two-way interaction. The significant two-way interaction among the effects of relative phase and increasing speed on mean error of relative phase warrants the rejection of Ho^2; therefore, a relationship was demonstrated among relative phase and increasing frequency for a bimanual coordination task. In contrast, the three-way interaction among the effects of sensory feedback, relative phase, and frequency on mean error of relative phase does not warrant the rejection of Ho^1. In contrast to previous findings (Cardoso de Oliveira & Barthelemy, 2005; Kazennikov et al., 2002; Serrien & Teasdale, 1996; Swinnen et al., 2000), the present study failed to reveal a clear role of sensory feedback for the bimanual coordination task or an interaction among sensory feedback, relative phase, and increasing frequency for the task.

Within Subjects Effect	SS	df	MS	F	p	Eta²
Phase	40045.48	1.00	40045.82	73.36	<.000**	.840
Error (phase)	7641.95	14.00	545.85			
Speed	26678.36	1.36	19648.93	48.95	<.000**	.778
Error (speed)	7630.41	19.01	401.42			
Feedback	310.95	2.24	138.68	1.13	.342	.074
Error (feedback)	3867.77	31.39	123.21			
Phase x Speed	20777.41	1.49	13915.84	41.69	<.000**	.749
Error (phase x speed)	6977.79	20.90	333.82			
Phase x Feedback	280.20	2.09	134.42	1.02	.375	.068
Error (phase x feedback)	3840.35	29.18	131.59			
Speed x Feedback	144.88	3.09	46.95	.505	.686	.035
Error (speed x feedback)	4015.17	43.19	92.95			
Phase x Speed x Feedback	101.92	3.43	29.72	.363	.806	.025
Error (phase x speed x feedback)	3935.68	48.01	81.98			

N=15

Table 5. Repeated measures ANOVA for phase (i.e., 0º and 180º relative phase patterns), speed (i.e., increasing frequency of oscillation), and feedback (i.e., 4 sensory feedback conditions) on mean error of relative phase. N=15 subjects, SS=sum of squares, df =degrees of freedom considering the Huynh-Feldt correction for sphericity, MS=mean square, F=test statistic, and p=significance level, Eta²=an indicator of effect size. The ** indicates a significant within subjects effect.

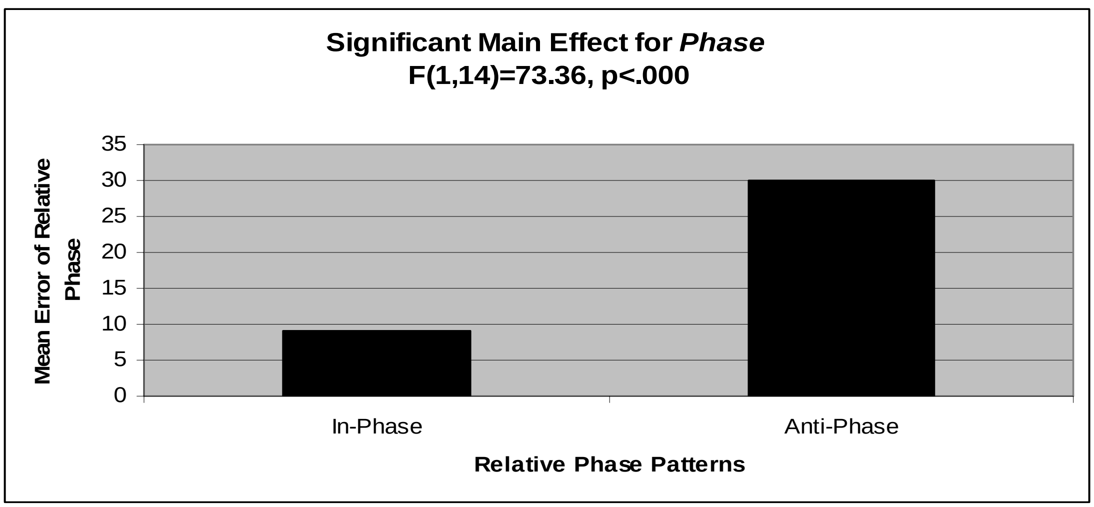

Figure 5. Significant main effect for phase. Mean error of relative phase as a function of in-phase (i.e., 0º relative phase pattern) and anti-phase (i.e., 180º relative phase pattern).

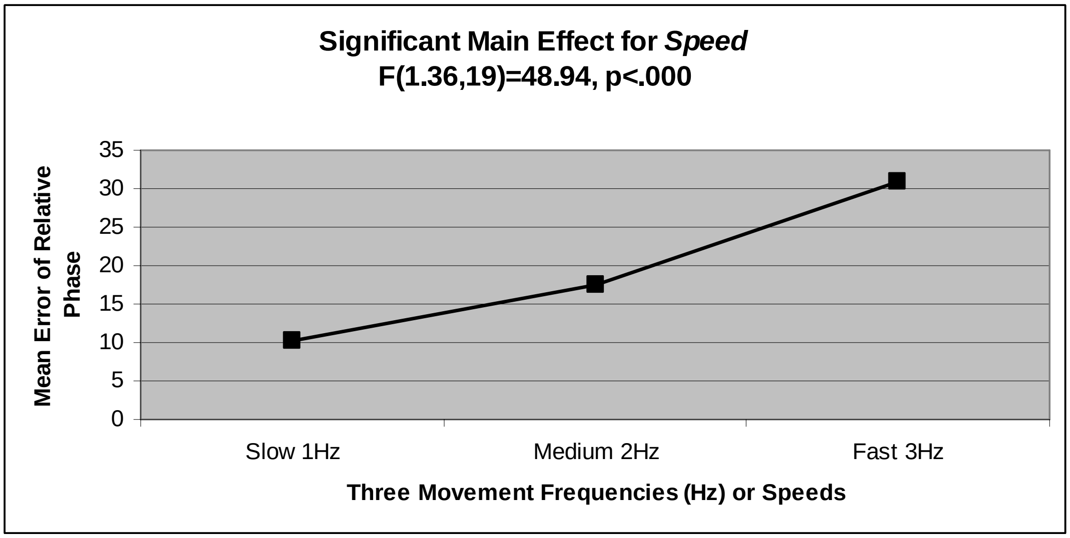

Figure 6. Significant main effect for speed. Mean error of relative phase as a function of speed or frequency of oscillation (i.e., slow (1Hz), medium (2Hz), and fast (3 Hz)).

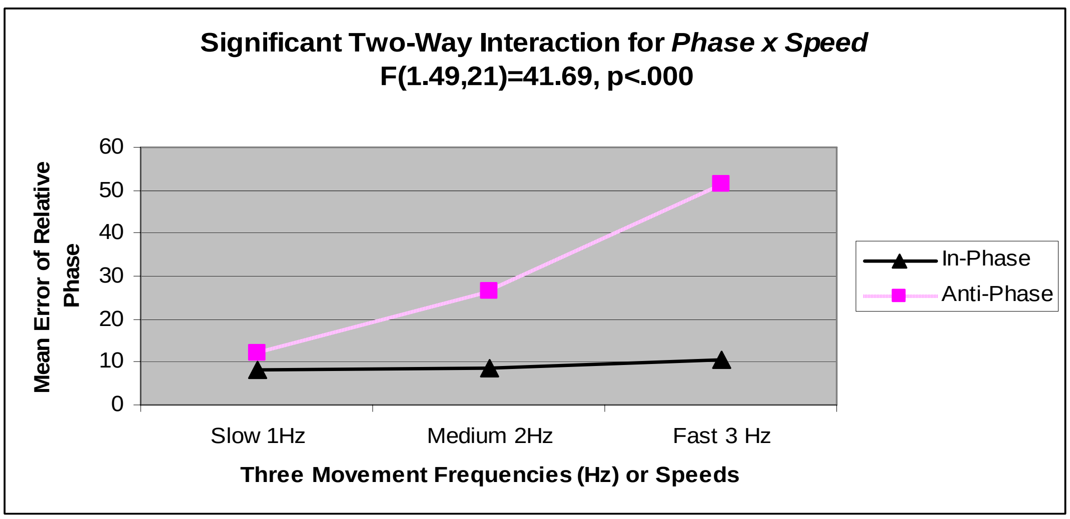

Figure 7. Significant two-way interaction for *phase x speed*. Mean error of relative phase as a function of speed or frequency of oscillation (i.e., slow (1Hz), medium (2Hz), and fast (3 Hz)) for the 0º in-phase pattern and the 180º anti-phase pattern.

The significant two-way interaction for *phase x speed* was further analyzed utilizing post hoc analysis of simple main effects using the Bonferroni correction, thereby determining the effects of one independent variable while holding the other independent variable constant. Determining the effects of the frequency of oscillation or speed (i.e., 1Hz, 2Hz, 3Hz) at a single relative phase pattern (i.e., 0º or 180º) is an example of a simple main effect. Considering the significant two-way interaction for *phase x speed*, 9 total pairings were tested to compare the 3 speeds within a single relative phase pattern (i.e., 3 speeds x 2 relative phase patterns = 6) and to compare the 2 phases within a single speed (i.e., 2 phases within 3 speeds = 3). Because 18 overall tests were performed, including 9 post hoc comparisons for mean error of relative phase and 9 post hoc comparisons for standard deviation of relative phase (further discussed in the next section), the critical p-value was adjusted to account for the 18 tests (.05/18=.0027, p-value=.0027).

Comparing slow (1Hz), medium (2Hz), and fast (3Hz) speeds within the 0º and 180º relative phase patterns, 3 pairwise comparisons were performed: slow versus medium, slow versus fast, and medium versus fast (see Tables 6 and 7).

Pairwise Comparisons for 0º In-phase Pattern	**df**	**t**	***p***
slow versus medium	32	.171	.865
slow versus fast	32	.685	.498
medium versus fast	32	.514	.611

Table 6. Pairwise comparisons for 0º in-phase pattern at slow (1Hz), medium (2Hz), and fast (3Hz) speeds. df=degrees of freedom for the t-distribution, t=test statistic, and p=significance level.

Pairwise Comparisons for 180º Anti-phase Pattern	**df**	**t**	***p***
slow versus medium	32	4.09	<.000**
slow versus fast	32	11.20	<.000**
medium versus fast	32	7.11	<.000**

Table 7. Pairwise comparisons for 180º anti-phase pattern at slow (1Hz), medium (2Hz), and fast (3Hz) speeds. df=degrees of freedom for the t-distribution, t=test statistic, and p=significance level. The ** indicates a significant pairwise comparison.

For the 0º in-phase pattern, the slow versus medium [t(32)=.171, *p*=.865], slow versus fast [t(32)=.685, *p*=.498], and medium versus fast [t(32)=.514, *p*=.611] pairwise comparisons were not significant suggesting that the 0º in-phase pattern was produced with the same amount of error across the slow, medium, and fast speeds (see Table 6 and Figure 7). For the 180º anti-phase pattern, the slow versus medium [t(32)=4.09, *p*<.000], slow versus fast [t(32)=11.20, *p*<.000], and medium versus fast [t(32)=7.11, *p*<.000] pairwise comparisons were all significant indicating that the performance of the 180º pattern was influenced by the increasing frequency or speed. Specifically, the 180º anti-phase pattern was produced with more error as speed increased (see Table 7 and Figure 7).

To compare the 0º and 180º relative phase patterns within a single speed, 3 pairwise comparisons were conducted: slow (1Hz), medium (2Hz), and fast (3Hz) (see Table 8).

Pairwise Comparisons for Phase within a Single Speed	**df**	**t**	***p***
0º versus 180º at slow speed	32	.27	.212
0º versus 180º at medium speed	32	.39	<.000**
0º versus 180º at fast speed	32	2.33	<.000**

Table 8. Pairwise comparisons for 0º and 180º relative phase patterns within a single speed; slow (1Hz), medium (2Hz), and fast (3Hz). df=degrees of freedom for the t-distribution, t=test statistic, and p=significance level. The ** indicates a significant pairwise comparison.

For the slow speed, the pairwise comparison was not significant [$t(32)=1.27$, $p=.212$]. The 0º and the 180º relative phase patterns, therefore, were produced with the same amount of error at the slow speed. At the medium and fast speeds, the pairwise comparisons were significant [$t(32)=5.39$, $p<.000$] and [$t(32)=12.33$, $p<.000$], respectively. As the speed increased from medium to fast, the 180º anti-phase pattern was produced with more error as compared to the 0º in-phase pattern (see Table 8 and Figure 7).

2.2.2 Dependent Variable: Standard Deviation of Relative Phase

Results for standard deviation of relative phase are shown in Tables 9-12 and in Figures 8-10. Findings mirrored those for mean error of relative phase. Specifically, the 180º anti-phase pattern was produced with more variability as frequency or speed of arm oscillation increased. In contrast, the variability of the 0º in-phase pattern was not influenced by the increasing frequency. The variability in performance of the relative phase patterns, however, was not influenced by the sensory feedback conditions.

The ANOVA for standard deviation of relative phase revealed significant main effects for *phase* [$F(1,14)=292.69$, $p<.000$] and *frequency* (indicated as "speed" in the Figure legends) [$F(2,28)=135.25$, $p<.000$] (see Table 9 and Figures 8 and 9). The main effect for *feedback* was not significant [$F(3,42)=.418$, $p=.741$]. A significant two-way interaction was shown for *phase x speed* [$F(1.85,25.87)=122.79$, $p<.000$] (see Table 9 and Figure 10). The three-way interaction for *phase x speed x feedback* [$F(4.06,56.88)=.366$, $p=.835$] was not significant. Eta squared, an indicator of effect size, was .954 and .906 for the significant main effects of phase and speed, respectively and .898 for the significant two-way interaction. The significant two-way interaction among the effects of relative phase and increasing speed on standard deviation of relative phase warrants the rejection of Ho^2; therefore, a relationship was shown among relative phase and increasing frequency or speed for a bimanual coordination task. In contrast, the three-way interaction among the effects of sensory feedback, relative phase, and speed on standard of relative phase does not warrant the rejection of Ho^1; therefore, no evidence was shown of a relationship among sensory feedback, relative phase, and increasing speed for a bimanual coordination task.

Within Subjects Effect	SS	df	MS	F	p	Eta²
Phase	12480.68	1.00	12480.68	292.69	<.000**	.954
Error (phase)	596.97	14.00	42.64			
Speed	9499.16	2.00	4749.58	135.25	<.000**	.906
Error (speed)	983.29	28.00	35.12			
Feedback	15.59	3.00	5.19	.418	.741	.029
Error (feedback)	522.49	42.00	12.44			
Phase x Speed	6250.54	1.85	3382.89	122.79	<.000**	.898
Error (phase x speed)	712.62	25.87	27.55			
Phase x Feedback	.054	3.00	.018	.002	1.00	.000
Error (phase x feedback)	490.94	42.00	11.69			
Speed x Feedback	14.95	4.01	3.73	.252	.908	.018
Error (speed x feedback)	830.73	56.13	14.79			
Phase x Speed x Feedback	19.54	4.06	4.81	.366	.835	.025
Error (phase x speed x feedback)	747.12	56.88	13.14			

N=15

Table 9. Repeated measures ANOVA for phase (i.e., 0º and 180º relative phase patterns), speed (i.e., increasing frequency of oscillation), and feedback (i.e., 4 sensory feedback conditions) on standard deviation of relative phase. N=15 subjects, SS=sum of squares, df =degrees of freedom considering the Huynh-Feldt correction for sphericity, MS=mean square, F=test statistic, and p=significance level, Eta²=an indicator of effect size. The ** indicates a significant within subjects effect.

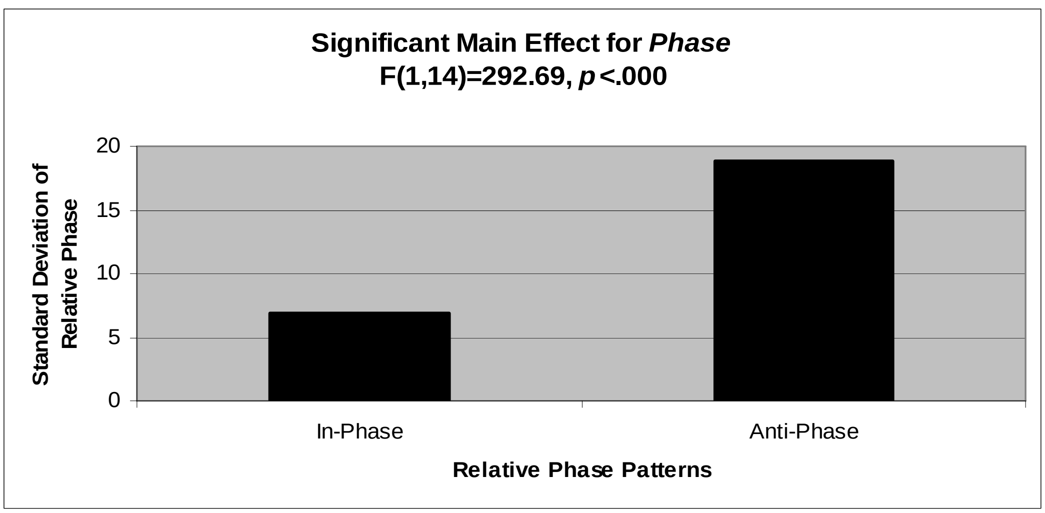

Figure 8. Significant main effect for phase. Standard deviation of relative phase as a function of in-phase (i.e., 0º relative phase pattern) and anti-phase (i.e., 180º relative phase pattern).

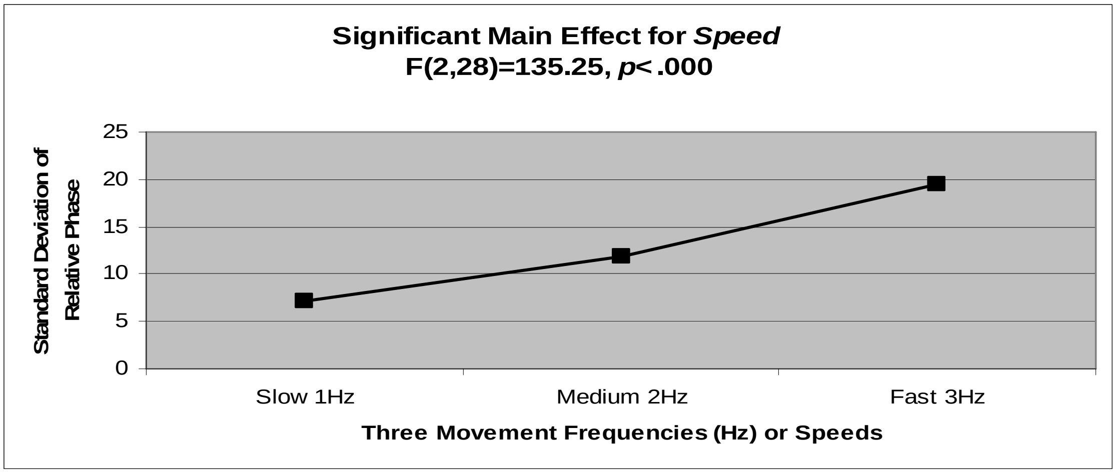

Figure 9. Significant main effect for speed. Standard deviation of relative phase as a function of speed or frequency of oscillation (i.e., slow (1Hz), medium (2Hz), and fast (3 Hz)).

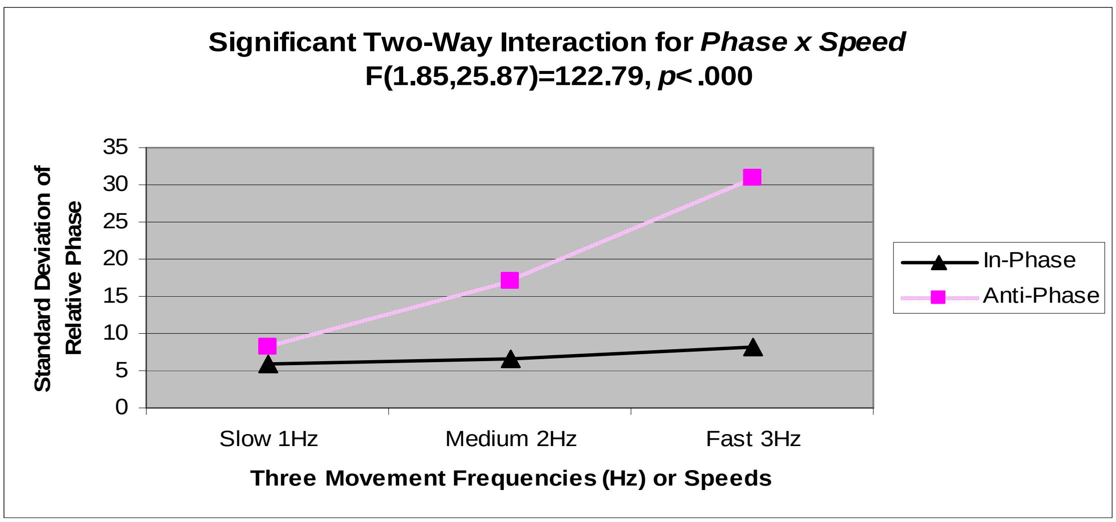

Figure 10. Significant two-way interaction for *phase x speed*. Standard deviation of relative phase as a function of speed or frequency of oscillation (i.e., slow (1Hz), medium (2Hz), and fast (3 Hz)) for the 0º in-phase pattern and the 180º anti-phase pattern.

The significant two-way interaction for *phase x speed* was further analyzed utilizing post hoc analysis of simple main effects using the Bonferroni correction. Similar, to the post hoc comparisons for mean error of relative phase, nine total pairings were tested (see Tables 10, 11, 12). Because 18 overall tests were performed, including the 9 post hoc comparisons for mean error of relative phase and 9 post hoc comparisons for standard deviation of relative phase, the critical p-value was adjusted to account for the 18 tests (.05/18=.0027, p-value=.0027).

Pairwise Comparisons for 0º In-phase Pattern	df	t	*p*
slow versus medium	32	.635	.529
Slow versus fast	32	2.27	.030
medium versus fast	32	1.64	.111

Table 10. Pairwise comparisons for 0º in-phase pattern at slow (1Hz), medium (2Hz), and fast (3Hz) speeds. df=degrees of freedom for the t-distribution, t=test statistic, and p=significance level.

Pairwise Comparisons for 180º Anti-phase Pattern	df	t	*p*
slow versus medium	32	8.64	<.000**
slow versus fast	32	22.12	<.000**
medium versus fast	32	13.48	<.000**

Table 11. Pairwise comparisons for 180º anti-phase pattern at slow (1Hz), medium (2Hz), and fast (3Hz) speeds. df=degrees of freedom for the t-distribution, t=test statistic, and p=significance level. The ** indicates a significant pairwise comparison.

Pairwise Comparisons for Phase within a Single Speed	df	t	*p*
0º versus 180º at slow speed	32	2.19	.035
0º versus 180º at medium speed	32	10.04	<.000**
0º versus 180º at fast speed	32	21.66	<.000**

Table 12. Pairwise comparisons for 0º and 180º relative phase patterns within a single speed; slow (1Hz), medium (2Hz), and fast (3Hz) speeds. df=degrees of freedom for the t-distribution, t=test statistic, and p=significance level. The ** indicates a significant pairwise comparison.

For the 0º in-phase pattern, all pairwise comparisons were not significant suggesting that the 0º in-phase pattern was produced with the same amount of variability across the slow, medium, and fast speeds (see Table 10 and Figure 10). For the 180º anti-phase pattern, all the pairwise comparisons were significant indicating that the variability in performance of the 180º pattern was influenced by the increasing speed. Specifically, the 180º anti-phase pattern was produced with more variability as the speed increased (see Table 11 and Figure 10).

For the comparison between 0º and 180º at the slow speed, the pairwise comparison was not significant [t(32)=2.19, *p*=.035] (see Table 12). The 0º and the 180º relative phase patterns, therefore, were produced with the same amount of variability at the slow speed. At the medium and fast speeds, the pairwise comparisons were significant [t(32)=10.04, *p*<.000] and [t(32)=21.66, *p*<.000], respectively. As the speed increased from medium to fast, the 180º anti-phase pattern was produced with more variability as compared to the 0º in-phase pattern (see Table 12 and Figure 10).

2.2.3 Summary

In conclusion, data for both mean error of relative phase and standard deviation of relative phase error failed to provide evidence that Ho^1 should be rejected. Thus, no evidence was obtained pointing to an interaction among sensory feedback condition, relative phase pattern, and frequency of bimanual oscillation. Moreover, no evidence was seen of an influence of feedback condition on bimanual coordination task performance in the present study. This finding is conceptually at odds with those reported by previous authors, who indicated a role of feedback in bimanual coordination control (Cardoso de Oliveira & Barthelemy, 2005; Kazennikov et al., 2002; Serrien & Teasdale, 1996; Swinnen et al., 2000).

In contrast, Ho^2 was rejected based on the present data set, suggesting that a relationship does exist between relative phase pattern and frequency of bimanual oscillation. Specifically, the 180º anti-phase pattern became less accurate and more variable when speed increased. The 0º in-phase pattern was not influenced by the increasing speed and was produced with the same accuracy and variability at all the speeds. The 0º in-phase pattern, therefore, was more accurate and more stable than the 180º anti-phase pattern. This finding replicates earlier ones indicating greater stability associated with the 0º pattern as compared to the 180º pattern (Kelso, 1984; Scholz & Kelso, 1989, 1990; Tuller & Kelso, 1989).

2.3 DISCUSSION

The purpose of Experiment 1 was to investigate the influence of sensory feedback on the coordination dynamics for an upper limb bimanual coordination task. Although it is generally acknowledged that sensory feedback is required to fine tune movement patterns (Bonnard & Pailhous, 1999; Cordo et al., 1995; Ghez & Sainburg, 1995; Jackson et al., 2002; Sainburg et al., 1993), its role in coordinative dynamics has received less attention. Moreover, recent evidence has raised the question that dynamic coordinative patterns may be fundamentally influenced by attention (Monno et al., 2000; Temprado et al., 2002; Temprado et al., 1999; Zanone et al., 2001; Zanone et al., 1999), perception (Mechsner et al., 2001; Mechsner & Knoblich, 2004) and sensory feedback (Cardoso de Oliveira & Barthelemy, 2005; Kazennikov et al., 2002; Serrien & Teasdale, 1996; Swinnen et al., 2000). The visual and auditory feedback conditions, therefore, were selected to investigate the role of sensory feedback connections on the coordinative dynamics of the 0º in-phase and the 180º anti-phase patterns.

Overall, results failed to indicate any clear role of visual or auditory feedback for performance on either the 0º in-phase or the 180º anti-phase movement patterns. One possibility for that failure is that the study was not adequately conducted to capture such effects. Although that possibility cannot be excluded, clear results in another corner of the study –regarding effects of frequency of bimanual oscillation– would seem to dampen the likelihood of it. Increasing speed of oscillation clearly influenced the performance of the 180º anti-phase pattern, but not the 0º in-phase pattern. As speed increased from slow to fast, the previously stable 180º anti-phase pattern destabilized, and was performed with increased variability and decreased accuracy. The 0º in-phase pattern, however, remained stable across frequency conditions. These findings replicate those from previous research (Kelso, 1984; Scholz & Kelso, 1989, 1990; Tuller & Kelso, 1989).

If the equipment and experimental procedures were not responsible for the acceptance of the null hypothesis for Ho[1], then perhaps an uncontrolled sensory feedback variable influenced the results. Although visual and auditory feedback was controlled in the present study, proprioceptive sensory feedback was not controlled. The influence of proprioceptive feedback, therefore, cannot be ruled out. In fact, the bimanual coordination task using the bimanual linear slide may not be governed by auditory and visual feedback, but rather by proprioceptive feedback. Salter and colleagues (2004) suggested that the friction of the bimanual linear slide and the reversal of movements in the horizontal plane may direct subjects' attention towards proprioceptive feedback from the upper limbs rather than visual and auditory feedback (Salter et al., 2004). In addition, Verschueren and colleagues (1999) suggested that proprioceptive feedback plays a role in the online monitoring of interlimb coupling for 0º and 180º relative phase patterns during cyclical bimanual movements in the horizontal plane (Verschueren, Swinnen, Cordo & Dounskaia, 1999). In contrast, a different bimanual task involving unidirectional circling movements may rely more on visual feedback rather than proprioceptive feedback (Mechsner et al., 2001). It seems possible that such discrepancies across studies may account for the difference in findings

Stated differently, the reliance on visual, auditory, and/or proprioceptive feedback in the performance of the 0º in-phase and the 180º anti-phase patterns may be task-specific. Consequently, if the correct feedback mechanism is identified for a given bimanual coordination task, then its perturbation should affect the performance of the relative phase patterns. Relative to the present study, the question can be asked whether relative phase would have been affected if proprioceptive feedback had been perturbed.

A study speaking to this possibility was conducted by Serrien and colleagues (1996). In that study, visual and proprioceptive feedback was varied for a bimanual coordination task involving the bimanual linear slide. Specifically, those authors manipulated visual and proprioceptive feedback during the production of 0º in-phase and 180º anti-phase patterns for young adult subjects (i.e., age rage 20-30 years) and elderly subjects (i.e., age range 66-77 years) at a slow speed (1 Hz) (Serrien, Teasdale, Bard & Fleury, 1996). To study the reliance on vision, the researchers manipulated the presence and absence of visual information with translucent liquid crystal glasses. The control of the opacity of the glasses was manipulated by computer and nearly instantaneous at the start of each trial. Proprioceptive feedback was varied by 2 electromagnetic vibrators that were secured to the lower arms. Vibratory stimulation was only provided to the right arm. The vibrators on the left arm served to provide similar weight conditions for both limbs. The vibratory stimulation activated the primary sensory endings of the muscle spindles to elicit proprioceptive messages that the central nervous system interpreted as real movement (Serrien et al., 1996). All of the subjects participated in 4 sensory feedback conditions: (a) vision and no vibration, (b) vision and vibration, (c) no vision and no vibration, and (d) no vision and vibration.

Results indicated that the young adult subjects demonstrated a decrease in pattern stability for the in-phase coordination mode during the no vibration conditions, whereas the in-phase patterns during the no vibration conditions were not affected for the elderly subjects. Even though young adults demonstrated a decrease in pattern stability during 0º in-phase coordination whereas older subjects did not, both groups were sensitive to proprioceptive influences during the 180º anti-phase coordination as demonstrated by decreased pattern stability. This finding led to the suggestion that the integration of afferent information may have a more prominent influence in the anti-phase pattern than in the in-phase pattern.

This suggestion was also consistent with a study by Kots and colleagues (1971), who investigated two-joint arm movements of patients with deafferented distal joints. The authors observed that with practice the subjects were able to perform the 0º in-phase pattern, whereas the 180º anti-phase pattern was difficult to execute even after practice.

In the study by Serrien and colleagues (Serrien et al., 1996), in addition to proprioceptive feedback, the role of visual feedback was also evaluated. With no visual feedback of the limbs, the young subjects produced destabilized in-phase movements, whereas with no visual feedback the young subjects produced more stable anti-phase patterns. The availability of visual feedback did not influence the performance of the elderly subjects. This finding from the Serrien and colleagues (1996) study that no visual feedback destabilized the in-phase pattern and stabilized the anti-phase pattern in young subjects, stands in direct contrast to findings of the current study where visual and auditory feedback did not influence the performance of the in- and anti-phase bimanual coordination patterns. In addition, the 0º in-phase and the 180º anti-phase patterns were produced with the same stability at the slow speed in the current study, but the Serrien and colleagues (1996) study reported that the in-phase and anti-phase patterns were produced with different stability measures at the slow speed. Findings from the present study, however, were more consistent with widely reported effects demonstrating stability of both the 0º in-phase and the 180º anti-phase patterns at the slow speed (Kelso, 1984; Scholz & Kelso, 1989, 1990; Tuller & Kelso, 1989).

The discrepancy in findings across the present study and the one reported by Serrien and colleagues (1996) may be related to two factors. First, in the study by Serrien and colleagues (1996), the combination of the proprioceptive and the visual feedback may have influenced the subjects' ability to integrate sensory information in a much different way as compared to the auditory and visual feedback combination in the present study. In fact, auditory feedback was not controlled in the study by Serrien and colleagues (1996). Second, visual feedback in the study by Serrien and colleagues (1996) was controlled by the opacity of glasses worn by the subject, whereas the visual feedback in the current study was manipulated by controlling the lights in the room and thus absolute visibility. The opacity of the glasses could have provided an additional distraction that influenced performance rather than visual feedback. Specifically, the opaque glasses only masked visual input in the study by Serrien and colleagues (1996), and based on the write-up, it cannot be excluded that subjects were able to see clearly above and below the glasses. In contrast, vision was totally obscured by the control of all light sources in the present study.

These discrepancies between the study by Serrien and colleagues (1996) and the current study could be pursued with appropriately designed studies. Of equal or greater interest is the pursuit of questions regarding the role of proprioceptive feedback on the coordination dynamics of a bimanual linear slide task. Future studies should be conducted to further explore such questions. Proprioceptive feedback could be disrupted by adding vibratory stimulation to one or both of limbs, and perhaps healthy subjects as well as age-matched subjects with disordered proprioceptive feedback loops could be evaluated for the task. Another option would be to identify a methodology for achieving a complete block of limb proprioception for the duration of the experiment. In sum, although the present study failed to show any clear role of sensory feedback on the bimanual coordination task, the role of visual, auditory, and proprioceptive feedback on the performance of coordination dynamics, as a function of specific task, remains an important question for continued research.

2.3.1 Limitations

The major limitation of the current study was that proprioceptive feedback was not considered in the experimental design. It is not clear if the results of the study were related to real findings or if they were influenced by uncontrolled proprioceptive feedback. The study should be performed again with control of visual, auditory, and proprioceptive feedback.

A second limitation concerns the ability to generalize to other populations beyond those studies. As was noted, the subject pool consisted of young females. Thus, results cannot be generalized to children, males, or geriatric females. Clearly, the study should be replicated with other populations.

A third limitation is that the study of sensory feedback in coordinative tasks should be extended to other domains, beyond bimanual limb coordination. Such extension is the focus of the second study described next.

3.0 CHAPTER 3: EXPERIMENT 2

3.1 RESEARCH METHODS

3.1.1 Purpose

The purpose of Experiment 2 was to assess the influence of (i) auditory feedback (i.e., normal auditory feedback versus masked auditory feedback by speech noise), (ii) voice quality (i.e., breathy, normal, and pressed voice qualities), (iii) increasing fundamental frequency (i.e., 220Hz, 277Hz, 349Hz, 440Hz, 554Hz, 698Hz, and 880Hz), and (iv) their interactions on motor performance for a voice coordination task.

3.1.2 Participants

Subjects were 21 vocally trained adult females, ages 18-35 years. Three of the 18 subjects had a mean age of 29 years and had 15 years or more of singing of experience that included private, classical voice training, choral singing, and solo singing on the stage. The rest of the 18 subjects had a mean age of 20 years and had at least 3 years of choral singing only. The sample size of 21 subjects was based on an anticipated large main effect between the "normal auditory feedback" and the "masked auditory feedback by speech noise" sensory feedback conditions at a 0.6 between conditions correlation coefficient. One rationale for limiting the study to females was to minimize the variability in the data for the voice task, as voicing characteristics including aerodynamic ones used in the present study may differ sharply across the genders (Holmberg, Hillman & Perkell, 1988). In addition, the laryngeal resistance values perceptually equivalent to breathy, normal, and pressed voice qualities used in the current voice study were based on vocally, trained females and it was unknown if the laryngeal resistance values would be maintained across genders and even across trained and untrained voice users (Grillo & Verdolini, in preparation). A further rationale for using females was clinical. Females are generally more susceptible to voice problems (for example; Russell, Oates & Greenwood, 1998; Miller & Verdolini, 1995). If the present research leads to investigations of clinical populations, the recruitment of females was most sensible.

Subjects were in general good health with self-report of normal hearing, with no current history of a voice disorder by their report and no evidence of voice abnormality on the day of testing, as judged by a licensed speech-language pathologist specialized in voice. Subjects matched the pitches of 220Hz, 277Hz, 349Hz, 440Hz, 554Hz, 698Hz, and 880Hz while sustaining an /a/ for 2 seconds as assessed by the speech-language pathologist. In addition, subjects enrolled in the study said they felt comfortable producing the target voice qualities over several trials at 880Hz. Pregnant females were excluded from the study because pregnancy may alter the coordination dynamics of the voice production system. Following appropriate Institutional Review Board approved procedures, subjects were recruited within the greater Pittsburgh community using flyers distributed through voice teachers and coaches as well as the Heinz Chapel Choir and the Greater Pittsburgh Bach Festival Choir.

3.1.3 Equipment and Software

The experimental set-up for Experiment 2 is presented in Figure 11. Aerodynamic data was captured using a Rothenberg (1973) circumferentially vented face mask manufactured by Glottal Enterprises with attached airflow and pressure transducers designed by Neil Szuminsky, Engineering Consultant. A microphone (Audio-Technica, ATR35s with a frequency response of 50-18,000 Hz) was inserted and secured by a plastic stopper into the open end of the face mask to record fundamental frequency and intensity. The microphone communicated to a Compaq Presario R3000 laptop computer via a Sound Blaster Audigy 2 ZS sound card with 192kHz/104dB signal-to-noise clarity. The pressure and flow transducers communicated via the data translation device (DT BNC Box USB 9800 series) to the laptop computer with a custom software program called Pressure Feedback that ran the experiment. A Casio CTK-491 keyboard was used to provide the specific pitch before each trial. Attached to the laptop running the experiment was a Dell flat screen monitor, which provided online feedback of fundamental frequency and intensity. The speech noise, low passed filtered with a frequency spectrum equal to the long-term average spectrum of speech (-12 dB per octave with cut-off frequency at 1 kHz), was used for the masked auditory feedback condition. The speech noise was delivered by a GSI Clinical Audiometer manufactured by WelchAllyn via Optimus Pro-155 stereo supra-aural headphones at an intensity of 95 dBSPL.

The software program that ran the experiment featured a calibration function and an experiment function. Relative to calibration, the equipment was calibrated for aerodynamic functions prior to each day's data collection using a Micro Tronics U2 manometer for pressure calibration and a Glottal Enterprises pneumotach calibration unit for airflow. Acoustic calibration was completed before data collection began using a sound level calibrator (General

Radio Company Type 1562A) at 500Hz. Acoustic calibration of the microphone was set at 114 dBSPL considering the close proximity of the microphone to the subjects' mouth. The pressure transducer's plastic, intraoral tubing used to capture intraoral pressure signals was changed before every subject after the flow head was cleaned with alcohol. The experiment function of the software program guided the experiment's timing, provided subjects online feedback of fundamental frequency and intensity, and calculated laryngeal resistance (i.e., subglottic pressure divided by average airflow cmH20/l/s), fundamental frequency, and intensity for use in later data analysis.

Figure 11. The experimental set-up for Experiment 2, the voice study.

3.1.4 Experimental Design

The experiment used a three-way, within-subjects repeated measures design. The 3 independent variables were: (1) voice quality (i.e., breathy, normal, and pressed), (2) increasing fundamental frequency (i.e., 220Hz, 277Hz, 349Hz, 440Hz, 554Hz, 698Hz, and 880Hz), and (3) sensory feedback conditions (i.e., normal auditory feedback versus masked auditory feedback by speech noise). The dependent variables were mean of laryngeal resistance (cmH2O/l/s) and standard deviation of laryngeal resistance (cmH2O/l/s) at each fundamental frequency. For experimental trials, order of voice coordination pattern and feedback condition was randomly determined within and across subjects (see Table 13).

Subject Number	Sensory Feedback	Voice Quality
1	12	123
2	21	231
3	21	312
4	12	123
5	12	132
6	12	231
7	21	321
8	12	132
9	21	321
10	21	132
11	12	123
12	12	132
13	21	312
14	21	213
15	21	312
16	12	321
17	21	312
18	12	213
19	21	312
20	21	132
21	21	231

Table 13. Order of the sensory feedback conditions and voice coordination patterns for the 21 subjects. For sensory feedback, 1= normal auditory feedback and 2= masked auditory feedback only. For voice quality, 1= normal voice, 2= breathy voice, and 3= pressed voice.

3.1.5 Procedures

Following informed consent, subjects completed screening procedures. For screening, subjects answered questions pertaining to age, years and type of vocal training, hearing acuity, and the possibility of being pregnant. In addition, subjects matched pitches while sustaining an /a/ for 2 seconds across the target fundamental frequencies; 220Hz, 277Hz, 349Hz, 440Hz, 554Hz, 698Hz, and 880Hz. Twenty-one subjects participated in screening procedures and all were enrolled in the study.

After passing the screening, subjects were oriented to the voice qualities and the target utterance for approximately 5 minutes. Subjects were introduced to the 3 different voice qualities, breathy, normal, and pressed by way of a brief verbal description and demonstration by the experimenter on the target consonant-vowel syllable string (/pi pi pi pi pi/). The experimenter provided exemplars and verbal descriptions of pressed, normal, and breathy voice qualities on the /i/ vowel, based on published descriptions of the voice types (Alku & Vilkman, 1996; Peterson et al., 1994) and extensive personal experience. Briefly, pressed voice was demonstrated and described as an extremely high effort phonation mode, with the perception of an almost completely closed airway, as if pushing. Normal voice was demonstrated and described as a spontaneous voicing mode without any attempts to manipulate usual voice production. Breathy voice was demonstrated and described as easy phonation, characterized by auditory air escapage during phonation, with the vocal folds more abducted than adducted. Subjects were then asked to practice producing the voice qualities on the target consonant-vowel syllable string /pi pi pi pi pi/ at 277Hz and at 554Hz. Although subjects had been provided with exemplars of each of the voice qualities, subjects were instructed to produce their own versions of the qualities for each utterance.

Following introduction of the voice qualities and the target utterance, subjects were oriented to the task. The task involved placing a vented mask firmly over the mouth and nose, and positioning plastic tubing connected to the pressure transducer intraorally, avoiding blockage of the tube by the tongue. A strap was placed around the subject's head and tightened to secure a tight seal with the subject's face. After the experimenter checked the mask positioning to verify the seal, the subject was trained to produce a five-syllable consonant-vowel syllable string (/pi pi pi pi pi/) at an approximate rate of 88 beats per minute (Holmberg et al., 1988). Output intensity, in dB, was intended to be held constant within subjects, based on initial calibrating trials to identify spontaneous comfortable intensity for each individual (Grillo &

Verdolini, in preparation). Fundamental frequency began at 220 Hz and increased in Major 3rd increments until 880 Hz was achieved for each voice quality. The fundamental frequency plateaus were 220 Hz, 277 Hz, 349 Hz, 440 Hz, 554 Hz, 698 Hz, and 880 Hz.

Frequency and intensity were monitored by the experimenter from computer screen displays. Fundamental frequency targets (+/- 10Hz from the intended frequency) were met for all frequencies except 880Hz under normal auditory feedback and 698Hz and 880Hz under masked auditory feedback. Intensity targets (i.e., +/-1dB from a comfortable intensity), however, were not met. The challenge of maintaining a constant, predetermined comfortable intensity that was based on a conversational pitch was simply too challenging for subjects, and it is moreover reasonable that this part of the task should have been challenging, given the known covariance of fundamental frequency and intensity (Debruyne & Buekers, 1998; Klingholz, 1992; Titze, 2000; Titze & Sundberg, 1992). The challenge around maintaining a comfortable intensity level for all trials was further increased by the introduction of masking, due to the Lombard effect (Ferrand, 2005; Garbe, Siegel & Pick, 1976). In light of these difficulties, subjects were encouraged to focus more on pitch (i.e., fundamental frequency) criteria as opposed to intensity targets during task production.

When subjects were finished being oriented to the task, they proceeded to experimental trials which involved repeated /pi pi pi pi pi/ trials. Each experimental trial involved 3 /pi pi pi pi pi/ sequences. Each of the 3 repetitions was separated by a 1-sec rest for a total time of 12-13 seconds for a complete trial. The first fundamental frequency of 220Hz was played on the keyboard and then the subject screen indicated “GO” for the initiation of the trial. After completion of the trial at 220Hz, the same required voice quality was repeated at 277Hz and subsequently 349Hz and so on until 880Hz was reached. Subjects received a 15-second rest between successive trials, and a 2-min rest before switching to the next voice quality target.

Subjects were encouraged to maintain the target pattern as best as possible throughout all trials. If the pattern destabilized, subjects were instructed to recapture it even mid-trial. Voice quality targets were randomized within and across subjects with the constraint that all subjects performed one voice quality target from 220 Hz to 880 Hz before moving to the next voice quality target (see Table 13). Subjects received online feedback from the computer regarding their ability to satisfy fundamental frequency and intensity criteria (+/-10 Hz for fundamental frequency, +/-1 dB for intensity). Feedback was presented in the form of a bar graph indicating the fundamental frequency and the intensity level target with the subject's actual production superimposed on the target. During the experiment, subjects did not receive computer-generated feedback related to the voice qualities and laryngeal resistance because the performance feedback may have influenced learning and confounded the results of the sensory feedback condition.

In addition to experimental trials just described, subjects also participated in two sensory feedback conditions: "auditory feedback" and "masked auditory feedback". The order of the sensory feedback condition was randomized within and across subjects (see Table 13). In the normal auditory feedback condition, subjects heard their voice productions with no interference. In the masked auditory feedback condition, subjects received speech noise presented to their ears via supra-aural headphones at 95 dBSPL in an effort to block out the subject's ability to hear their own voice. As determined during piloting of the experimental set-up, the intensity level of the speech noise masker was effective in masking voice without causing discomfort to the subjects. The speech noise was low passed filtered with a frequency spectrum equal to the long-term average spectrum of speech (-12 dB per octave with cut-off frequency at 1 kHz) and was equivalent to the standardized noise typically used for masking speech (IEC, 1979). In brief, low-pass filtered speech noise effectively masks bone conduction because bone conduction predominantly transmits low frequencies (Natke & Kalveram, 2001). There was no simple way of physically measuring the effectiveness of bone conduction; therefore, the experimenter relied on the subjects' observations as to whether or not they could hear their voice productions (Natke & Kalveram, 2001). In addition, large, cup-like supra-aural headphones were used to minimize transmission of the air-conducted signal (Kiran & Larson, 2001).

3.1.6 Data Reduction

Data reduction involved several steps, which were automatized using custom-made software (Szuminsky, Engineering Consultant). Subglottic pressures were estimated from oral pressures for each trial using custom software that obtained the interpolated pressure between pressure peaks 2 and 3, 3 and 4, and 4 and 5 for each /pi pi pi pi pi/ string, as well as the time-locked average flow for those syllables, fundamental frequency, and intensity level. Laryngeal resistance (i.e., subglottic pressure divided by average airflow, cmH20/l/s) was calculated from the combination of the estimated subglottic pressure value and subsequent average airflow value between peaks 2 and 3, 3 and 4, 4 and 5 for each /pi pi pi pi pi/ string. Summary files were generated by the software program that indicated means and standard deviations of laryngeal resistance, fundamental frequency, and intensity. Similar to the data reduction approach in Experiment 1 on bimanual coordination, the mean of laryngeal resistance and standard deviation of laryngeal resistance were calculated for each fundamental frequency trial. Mean of laryngeal resistance and standard deviation of laryngeal resistance were used in statistical analyses.

For Experiment 1, mean error of relative phase was used as a dependent variable because subjects were required to produce 2 numeric standards of 0º relative phase and 180º relative phase. For Experiment 2, subjects were required to produce perceptual standards of laryngeal resistance not numeric standards of laryngeal resistance, so mean error of laryngeal resistance could not be calculated. Thus, mean of laryngeal resistance and standard deviation of laryngeal resistance were used in data analysis.

3.1.7 Statistical Analysis

Statistical analyses were guided by the study's purpose. The purpose of Experiment 2 was to extend the inquiry of motor control beyond the typical bimanual coordination domain, as demonstrated in Experiment 1, to a task that required respiratory and laryngeal coordination for the production of voice. Specifically, Experiment 2 investigated the role of sensory feedback (i.e., audition) on the coordination dynamics of a voice task involving laryngeal resistance (i.e., subglottic pressure divided by average airflow, cmH20/l/sec).

A three-way, repeated measures analysis of variance (ANOVA) was conducted on each of the dependent variables. The independent variables were the sensory feedback conditions (i.e., normal auditory feedback versus masked auditory feedback by speech noise), voice qualities (i.e., breathy, normal, and pressed), and increasing fundamental frequency or pitch (i.e., 220Hz, 277Hz, 349Hz, 440Hz, 554Hz, 698Hz, and 880Hz). The dependent variables were the mean laryngeal resistance and the standard deviation of laryngeal resistance. Significance level was set at $\alpha = .05$ and post hoc simple main effects were analyzed using the Bonferroni correction. The ANOVAs were used to test the following two statistical hypotheses *(Ho)*:

1. Ho^1: There is no significant interaction among the effects of 2 sensory feedback conditions (i.e., normal auditory feedback versus masked auditory feedback by speech noise), 3 voice qualities (i.e., breathy, normal, and pressed), and increasing fundamental frequency or pitch (i.e., 220Hz, 277Hz, 349Hz, 440Hz, 554Hz, 698Hz, and 880Hz) on mean laryngeal resistance and/or standard deviation of laryngeal resistance.
2. Ho^2: There is no significant interaction among the effects of 2 sensory feedback conditions (i.e., normal auditory feedback versus masked auditory feedback by speech noise) and 3 voice qualities (i.e., breathy, normal, and pressed) on mean laryngeal resistance and/or standard deviation of laryngeal resistance.

3.2 RESULTS

Similar to Experiment 1, the following assumptions were applied to the within-subjects repeated measures design: (1) sphericity, (2) normality, and (3) independence by random order of the design. To correct for sphericity, the Huynh-Feldt (1970) correction was used for all tests. The normality assumption was met for some of the mean and standard deviation values, but not for all. Non-normality, however, has very little effect on the level of significance and the power of the *F*-test in the analysis of variance (ANOVA) when considering non-directional tests (Glass and Hopkins, 1996). Thus, the data were not adjusted for normality. It is more important to meet the assumption of independence by random order of the design as its violation may seriously affect the level of significance and the power of the *F*-test (Glass and Hopkins, 1996). (3) The assumption of independence by random order of the design was met by the random order of the 2 sensory feedback conditions and the 3 voice patterns. Alpha was set at .05 for all analyses and adjusted appropriately for the number of post hoc comparisons.

Data from 18 out of the total 21 subjects were used in the ANOVAs. Stem and leaf plots of the data indicated that subjects 17, 19, and 20 (i.e., 3 total) had mean and standard deviation values that were extreme outliers as a function of all 3 independent variables. The consistent extreme outliers for the 3 subjects may be explained by their level of vocal expertise and also by their age. Subjects 17, 19, and 20 all had 15 years and more of vocal experience which involved private, classical vocal training, singing in choirs, and solo singing on the stage. Conversely, the rest of the 18 subjects had at least 3 years of choral singing experience with no private, vocal training. The 3 subjects were older (e.g., mean age of 29) as compared to the 18 subjects (e.g., mean age of 20) and arguably had more time to focus on vocal training. In addition, subject 17 had a difficult time achieving a tight seal between the airflow mask and the arch of the nose. The extremely elevated mean and standard deviation values for subject 17, therefore, may also be related to airflow escaping around the mask causing invalid airflow data. Even with a tight seal between the arch of the nose and the airflow mask, subjects 19 and 20 had elevated means and standard deviations of laryngeal resistance that were consistent with subject 17. After analysis of the data, subjects 17, 19, and 20 performed extremely differently from the other 18 subjects; therefore, data from subjects 17, 19, and 20 were excluded from the ANOVAs. Mean and standard deviation values of the 3 subjects excluded from the ANOVAs will be analyzed descriptively later on in the results section.

The results that follow indicate findings for (1) analysis of laryngeal resistance values compared to previous data, (2) analysis of fundamental frequency and intensity targets, (3) standard deviation of laryngeal resistance, (4) mean of laryngeal resistance, and (5) descriptive analysis of subjects 17, 19, and 20.

3.2.1 Analysis of Laryngeal Resistance Values Compared to Previous Data

In a prior study, Grillo and Verdolini (in preparation) demonstrated that laryngeal resistance (i.e., subglottic pressure divided by average airflow cmH20/l/sec) was able to distinguish the voice qualities of breathy, normal, and pressed in a cohort of trained adult female vocalists. The conclusion was that laryngeal resistance was a valid measure that reflected the synergistic relations among the respiratory and laryngeal subsystems of voice production. Results from the study by Grillo and Verdolini (in preparation) established sample means and 95% confidence intervals that could cover the population parameter of μ for breathy, normal, and pressed voice qualities by laryngeal resistance (cmH20/l/sec) (see Table 14). In the current study, the means and the 95% confidence intervals for each voice quality were similar to the means and 95% confidence intervals of laryngeal resistance previously reported (Grillo and Verdolini, in preparation). The breathy voice quality was produced with the lowest laryngeal resistance value and the smallest confidence interval, whereas the pressed voice quality was produced with the highest laryngeal resistance value and the largest confidence interval (see Table 14). The progression of the data for laryngeal resistance from the smallest laryngeal resistance targets in breathy voice to the largest laryngeal resistance targets in pressed voice, therefore, was consistent with the progression of laryngeal resistance in a previous study (Grillo and Verdolini, in preparation).

Grillo & Verdolini (in preparation)	**Sample Mean**	**95% Confidence Intervals**
Laryngeal Resistance, breathy	11.84	10.35, 13.33
Laryngeal Resistance, normal	41.98	33.04, 50.93
Laryngeal Resistance, pressed	463.83	258.31, 669.35
Current Study	**Sample Mean**	**95% Confidence Intervals**
Laryngeal Resistance, breathy	43.76	33.48, 54.04
Laryngeal Resistance, normal	79.85	57.42, 102.28
Laryngeal Resistance, pressed	213.16	124.28, 302.030

Table 14. Sample mean and 95% confidence intervals that could cover the population parameter of μ for breathy, normal, and pressed voice qualities by laryngeal resistance (cm H2O/l/s) in a prior study (Grillo & Verdolini, in preparation) and the current study with data from 18 subjects.

3.2.2 Analysis of Fundamental Frequency and Intensity Level Targets

A goal for data collection in the present study was for subjects to maintain constant fundamental frequency (pitch) and intensity (loudness) throughout all production trials. Information about fundamental frequency and intensity was provided to subjects, online, during all productions. The following tables and figures indicate the results. Data about fundamental frequency are presented first in Table 15 and in Figures 12-14 and are followed by data for intensity in Table 16 and in Figures 15-17.

As demonstrated in Table 15 and Figures 12-14, subjects met the target fundamental frequency criteria (i.e., +/-10Hz from the target Fo) across the 3 voice qualities for frequencies 220Hz, 277Hz, 349Hz, 440Hz, 554Hz, and 698Hz –but not for 880Hz– under the normal auditory feedback condition. In the masked auditory feedback condition, subjects met the fundamental frequency criteria across the 3 voice qualities for all the frequencies except 698Hz and 880Hz. Considering the semitone pitch range, however, frequency targets were met for all frequencies across both of the sensory feedback conditions. For the two highest frequency targets, the semitone pitch range is 830.6-932.3Hz for 880Hz and 659.3-740.0Hz for 698Hz. Thus, the 2 highest frequencies produced by the subjects across normal and masked auditory feedback were within the semitone pitch range (see Table 15).

Target Pitch & Normal Feedback	**Breathy**	**Normal**	**Pressed**	**Target Pitch & Masked Feedback**	**Breathy**	**Normal**	**Pressed**
220	220.88	219.76	221.43	220	220.01	224.39	223.29
277	277.26	277.96	274.82	277	276.05	277.51	275.22
349	348.89	347.93	350.08	349	347.19	350.11	350.49
440	440.39	439.62	438.70	440	442.67	437.16	436.97
554	554.97	557.06	557.14	554	554.77	552.62	548.23
698	688.07	696.82	699.11	698	683.07	684.76	672.93
880	866.64	867.78	856.76	880	837.30	843.22	841.36

Table 15. Means of fundamental frequency (Hz) for each voice coordination pattern at the target 7 fundamental frequencies (Hz) under normal auditory feedback and masked auditory feedback for 18 subjects.

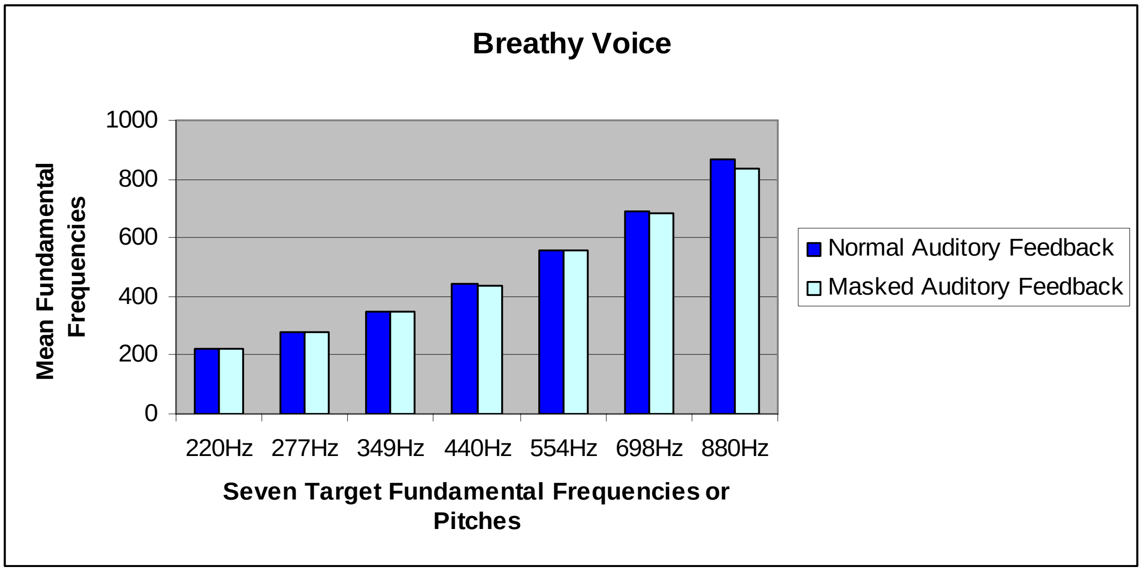

Figure 12. Breathy voice produced at the seven target fundamental frequencies (Hz) under normal and masked auditory feedback conditions. Mean fundamental frequencies (Hz) produced by the 18 subjects as a function of the seven target fundamental frequencies (Hz) for normal and masked auditory feedback.

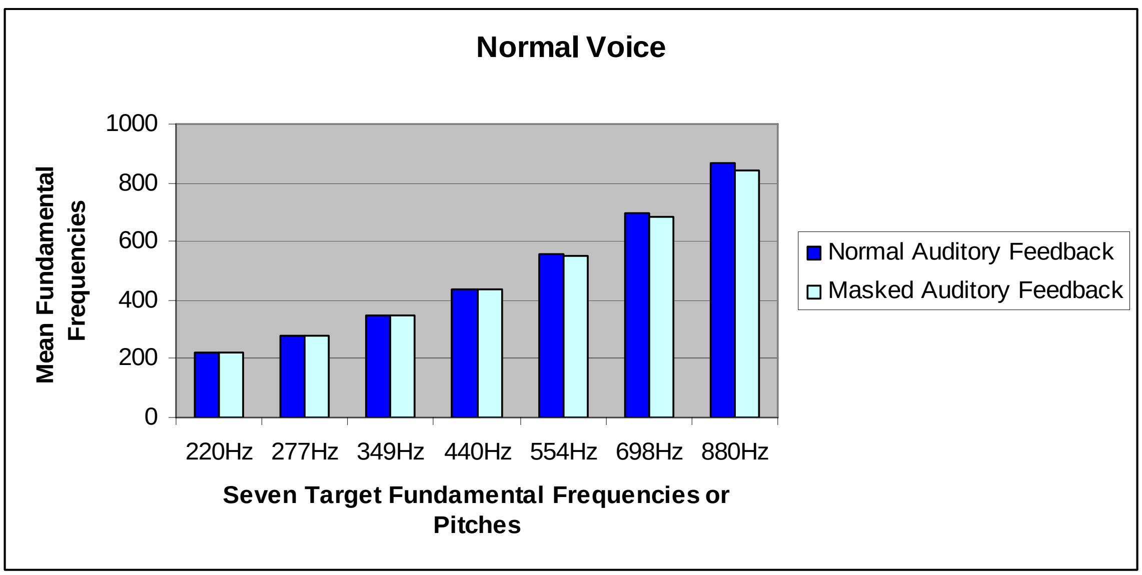

Figure 13. Normal voice produced at the seven target fundamental frequencies (Hz) under normal and masked auditory feedback conditions. Mean fundamental frequencies (Hz) produced by the 18 subjects as a function of the seven target fundamental frequencies (Hz) for normal and masked auditory feedback.

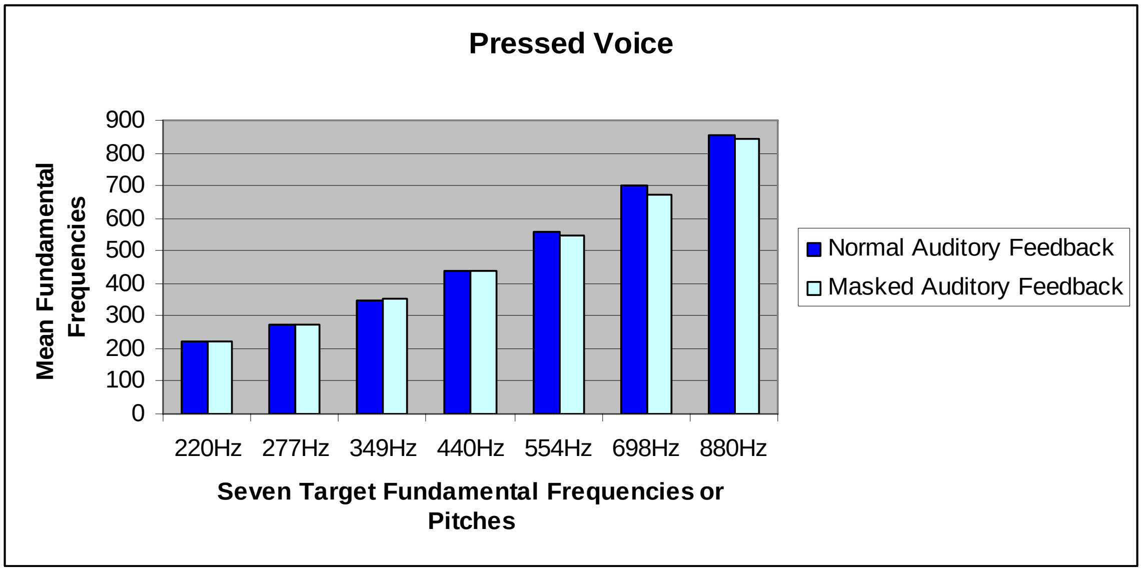

Figure 14. Pressed voice produced at the seven target fundamental frequencies (Hz) under normal and masked auditory feedback conditions. Mean fundamental frequencies (Hz) produced by the 18 subjects as a function of the seven target fundamental frequencies (Hz) for normal and masked auditory feedback.

Regarding results for intensity, a well-known effect is that as fundamental frequency increases, intensity level also increases (Debruyne & Buekers, 1998; Klingholz, 1992; Titze, 2000; Titze & Sundberg, 1992). In addition, the Lombard effect describes the familiar phenomenon that voice intensity tends to increase under noise conditions – or masking (Ferrand, 2005; Garbe, Siegel & Pick, 1976). In the present study, subjects produced utterances over a two-octave fundamental frequency range. If the target intensity had been established for each subject at the outset of the study as a high intensity, there might have been some chance that subjects could have maintained a constant intensity across trials. The fact that a "comfortable" intensity was established as the target; however, virtually guaranteed that subjects would fail to consistently produce that intensity at higher frequencies. In fact, phonetogram data show that both minimum and maximum intensities tend to be considerably larger for high as compared to low fundamental frequencies (Klingholz, 1992). This feature of the experiment is admittedly a design flaw, which was aggravated by the Lombard effect as 95 dBSPL speech noise masking was introduced.

Even though subjects were unable to hold intensity level constant (i.e., +/-1dB around a comfortable intensity level), the mean intensity level appeared to remain consistent across the 3 voice qualities with a gradual increase in intensity as fundamental frequency increased (see Table 16). In addition, the masked auditory feedback condition for all 3 voice qualities facilitated an increase in intensity level as compared to the normal auditory feedback condition (see Figures 15-17). The changes in intensity level across each of the voice qualities, therefore, appeared to be related to the increase in fundamental frequency and the specific sensory feedback condition rather than the voice qualities themselves.

Target Pitch & Normal Feedback	**Breathy**	**Normal**	**Pressed**	**Target Pitch & Masked Feedback**	**Breathy**	**Normal**	**Pressed**
220	104.40	102.53	99.45	220	107.06	108.28	105.35
277	105.98	105.53	103.57	277	109.53	109.08	107.22
349	109.74	112.71	111.20	349	113.31	115.86	113.19
440	114.24	118.23	117.78	440	117.78	116.51	119.55
554	119.41	123.58	120.98	554	125.81	129.62	123.71
698	121.11	127.37	123.44	698	131.36	136.74	130.83
880	125.82	129.44	124.64	880	137.68	140.28	133.81

Table 16. Means of intensity level (dBSPL) for each voice coordination pattern at the target 7 fundamental frequencies (Hz) under normal auditory feedback and masked auditory feedback for 18 subjects.

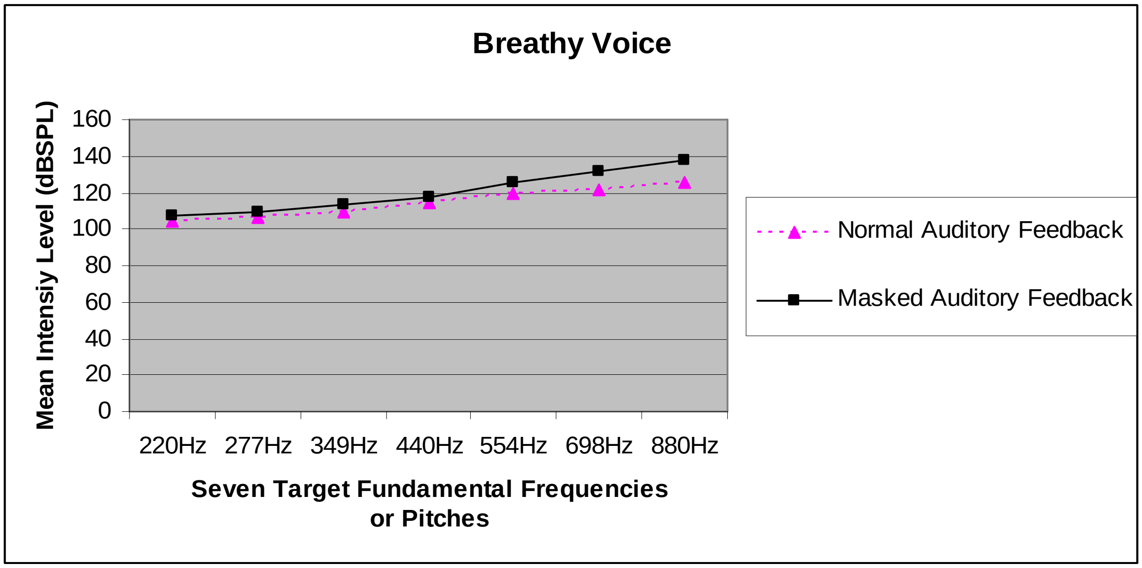

Figure 15. Breathy voice produced at the seven target pitches (Hz) under normal and masked auditory feedback conditions. Mean intensity level (dBSPL) produced by the 18 subjects as a function of the 7 target fundamental frequencies (Hz) for normal and masked auditory feedback.

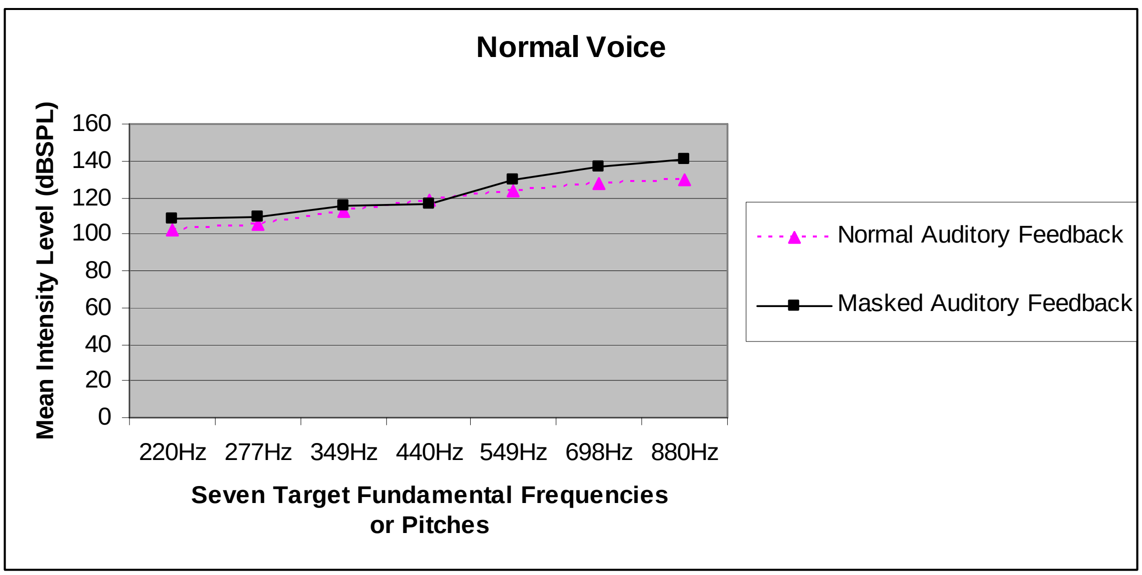

Figure 16. Normal voice produced at the seven target pitches (Hz) under normal and masked auditory feedback conditions. Mean intensity level (dBSPL) produced by the 18 subjects as a function of the 7 target fundamental frequencies (Hz) for normal and masked auditory feedback.

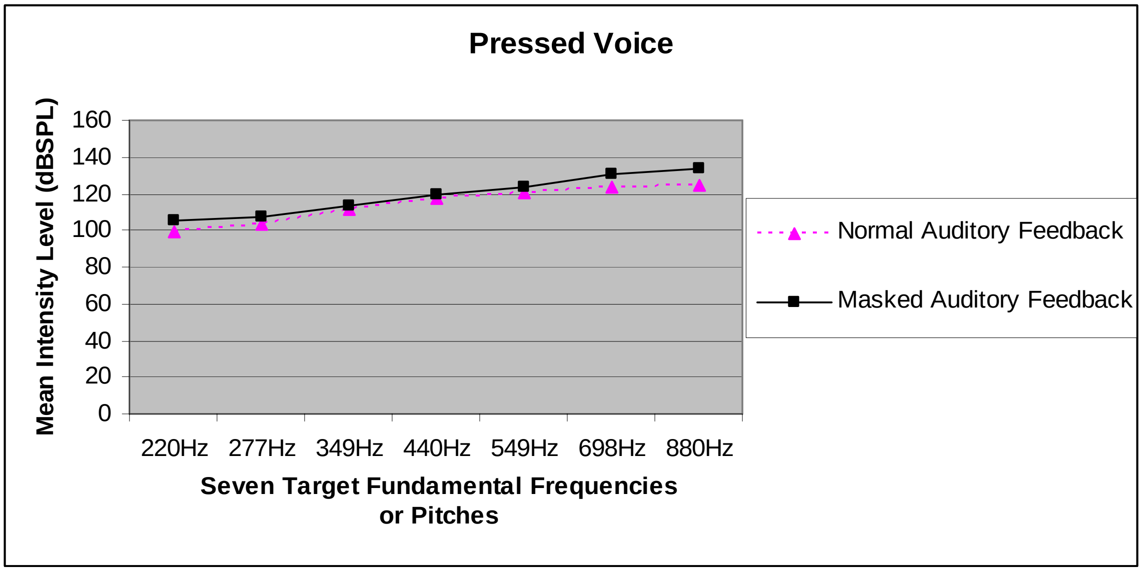

Figure 17. Pressed voice produced at the seven target pitches (Hz) under normal and masked auditory feedback conditions. Mean intensity level (dBSPL) produced by the 18 subjects as a function of the 7 target fundamental frequencies for normal and masked auditory feedback.

3.2.3 Dependent Variable: Standard Deviation of Laryngeal Resistance

Results for standard deviation of laryngeal resistance are shown in Table 17 and in Figures 18-22. Overall, standard deviation of laryngeal resistance was greatest for the pressed voice quality as compared to the breathy and normal voice qualities suggesting that the pressed voice quality is inherently unstable. In addition, standard deviation of laryngeal resistance was increased in the masked auditory feedback condition as compared to the normal auditory feedback condition. The variability in performance of the 3 voice qualities, therefore, did vary with feedback condition.

The ANOVA for standard deviation of laryngeal resistance revealed significant main effects for *quality* [F(1.03,17.50)=6.98, *p*=.016] and *feedback* [F(1,17)=6.04, *p*=.025] (see Table 17 and Figures 18 and 19). The main effect for *pitch* [F(1.79,30.44)=.869, *p*=.419] was not significant. Neither the two-way interaction for *quality x feedback* [F(1.07,18.19)=3.59, *p*=.072] nor the three-way interaction for *quality x pitch x feedback* [F(1.59,27.09)=.803, *p*=.433] were significant. The two-way interaction for *quality x feedback*, however, approached significance at *p*=.072 with an observed power of .448. Eta squared, an indicator of effect size, was .291 and .262 for the significant main effects of quality and feedback, respectively. No evidence was found to warrant the rejection of either Ho^1 or Ho^2. Stated differently, no evidence was found of a relationship between voice quality, feedback condition, and fundamental frequency, nor for voice quality and feedback condition, in relation to standard deviation of laryngeal resistance.

Within Subjects Effect	**SS**	**df**	**MS**	**F**	**p**	**Eta²**
Quality	1636650.03	1.03	1589505.72	6.98	.016**	.291
Error (quality)	3982957.38	17.50	227542.75			
Pitch	156461.58	1.79	87387.11	.869	.419	.049
Error (pitch)	3061229.06	30.44	100574.19			
Feedback	316287.54	1.00	316287.54	6.04	.025**	.262
Error (feedback)	890025.99	17.00	52354.47			
Quality x Pitch	261299.79	1.66	157715.31	.689	.484	.039
Error (quality x pitch)	6442664.40	28.17	228744.88			
Quality x Feedback	459823.47	1.07	429854.22	3.59	.072	.174
Error (quality x feedback)	2176363.99	18.19	119677.55			
Pitch x Feedback	203561.28	1.74	117043.51	.984	.375	.055
Error (pitch x feedback)	3516048.56	29.57	118920.88			
Quality x Pitch x Feedback	282261.74	1.59	177094.31	.803	.433	.045
Error (quality x pitch x feedback)	5976210.31	27.09	220561.42			

N=18

Table 17. Repeated measures ANOVA for quality (i.e., breathy, normal, and pressed voice qualities), pitch (i.e., increasing fundamental frequency), and feedback (i.e., normal versus masked auditory feedback) on standard deviation of laryngeal resistance. N=18 subjects, SS=sum of squares, df =degrees of freedom considering the Huynh-Feldt correction for sphericity, MS=mean square, F=test statistic, and p=significance level, Eta²=an indicator of effect size. The ** indicates a significant within subjects effect.

In Figure 18, the pressed voice pattern had the largest standard deviation in performance as compared to the breathy and normal voice patterns perhaps indicative of its inherent instability. The breathy and the normal voice qualities appeared to be more stable with smaller standard deviations.

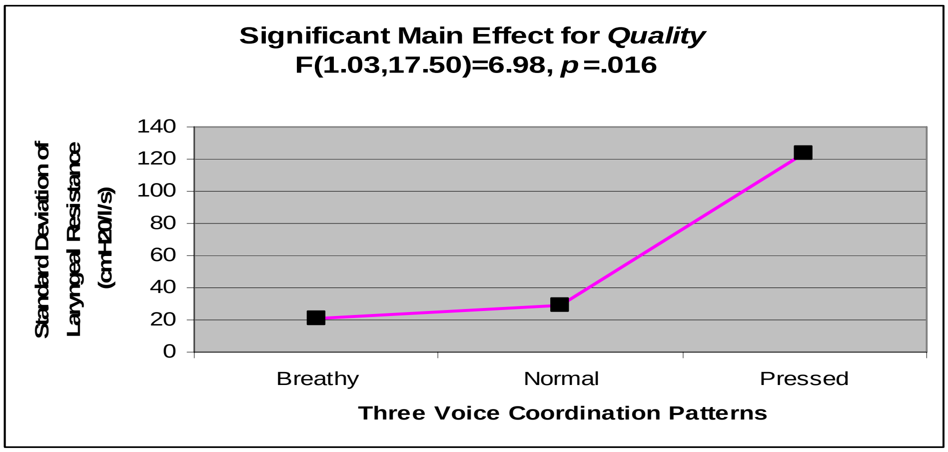

Figure 18. Significant main effect for quality. Standard deviation of laryngeal resistance (cmH2O/l/s) as a function of voice coordination pattern (i.e., breathy, normal, and pressed).

In Figure 19, the masked auditory feedback condition facilitated larger standard deviations of laryngeal resistance as compared to the normal auditory feedback condition. When auditory feedback was masked by speech noise, subjects' productions of the voice qualities were more variable. Thus, in contrast to Experiment 1 that assessed bimanual coordination, Experiment 2 demonstrated that sensory feedback influenced coordinative performance for a different task (i.e., voice coordination).

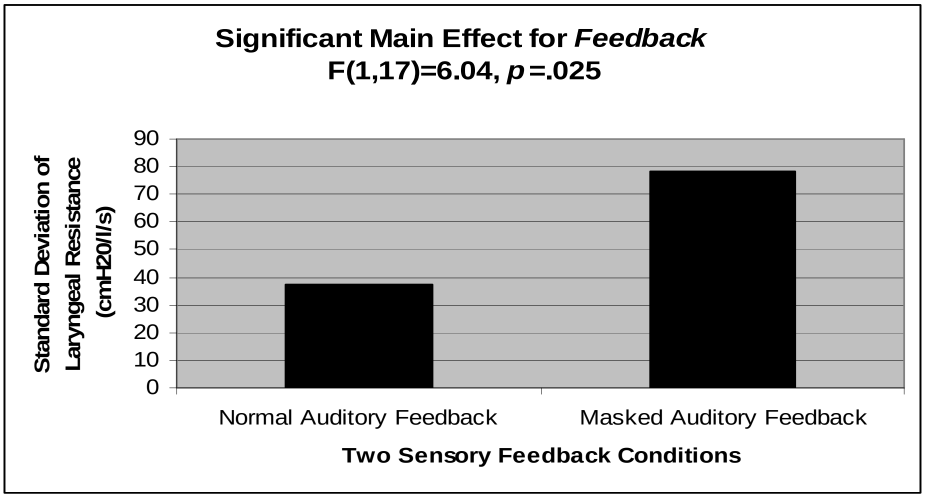

Figure 19. Significant main effect for feedback. Standard deviation of laryngeal resistance (cmH2O/l/s) as a function of sensory feedback condition (i.e., normal auditory feedback versus masked auditory feedback by speech noise).

Even though the *quality x feedback* two-way interaction was not significant for standard deviation of laryngeal resistance, the results for laryngeal resistance under the feedback conditions looked similar to the significant results of the *quality x feedback* interaction for mean of laryngeal resistance presented shortly. Specifically, the pressed voice quality was produced with more variability in the masked auditory feedback condition than in the normal auditory feedback condition (see Figure 20). In contrast, the variability of performance between the masked and normal auditory feedback conditions for the breathy and normal voice qualities appeared similar (see Figures 21 and 22). The masked auditory feedback condition, therefore, only influenced the variability in performance of the pressed voice quality, which was generally less stable than the other qualities. The breathy and normal voice qualities remained stable regardless of the sensory feedback condition.

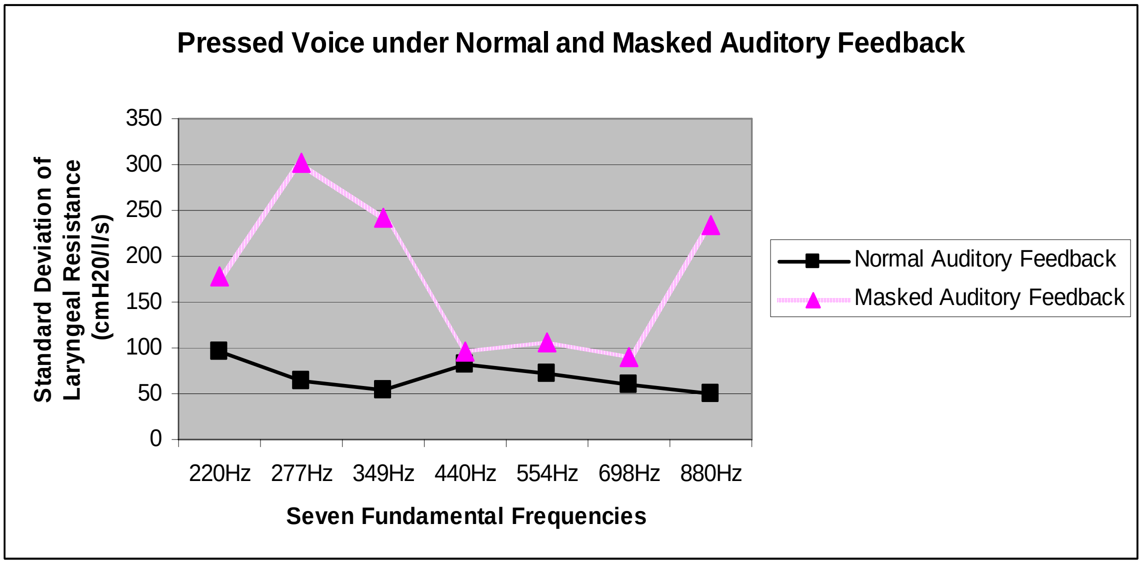

Figure 20. Pressed voice under normal and masked auditory feedback. Standard deviation of laryngeal resistance (cmH2O/l/s) as a function of seven fundamental frequencies (Hz) or pitches for pressed voice under normal and masked auditory feedback.

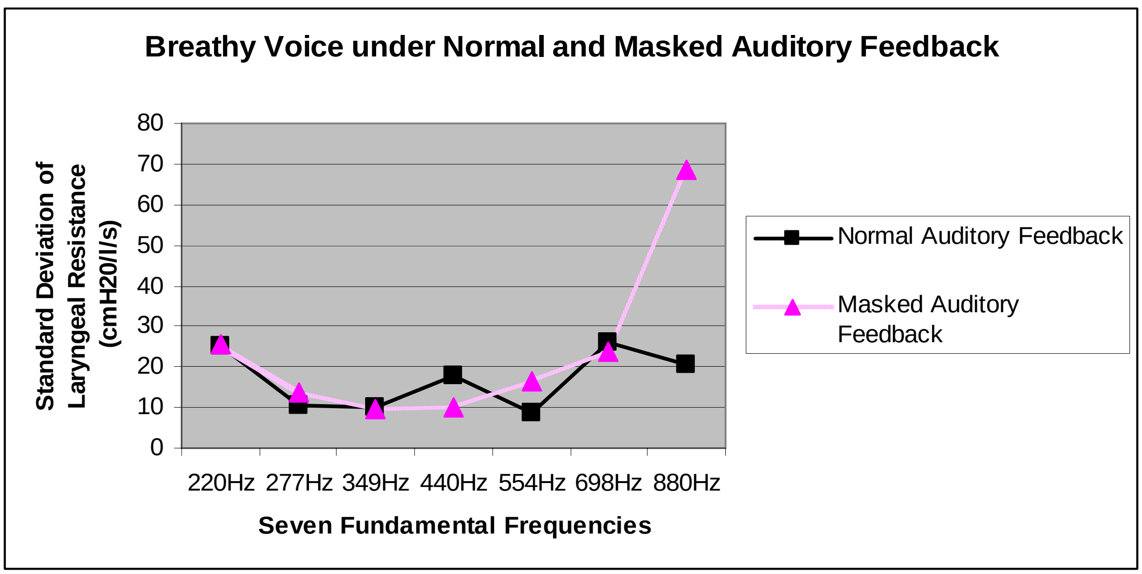

Figure 21. Breathy voice under normal and masked auditory feedback. Standard deviation of laryngeal resistance (cmH2O/l/s) as a function of seven fundamental frequencies (Hz) or pitches for breathy voice under normal and masked auditory feedback.

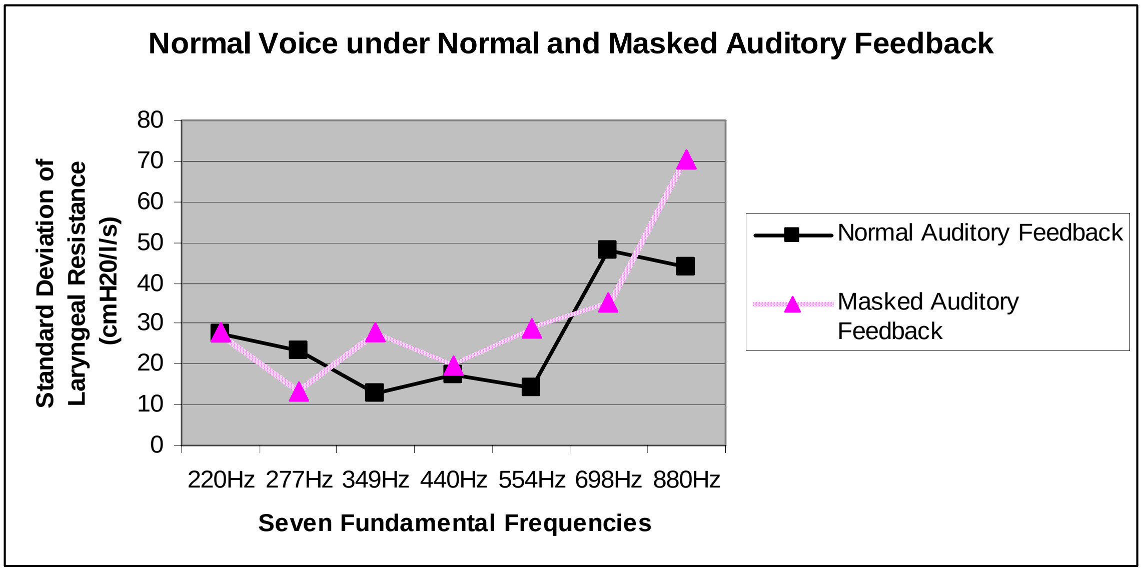

Figure 22. Normal voice under normal and masked auditory feedback. Standard deviation of laryngeal resistance (cmH2O/l/s) as a function of seven fundamental frequencies (Hz) or pitches for normal voice under normal and masked auditory feedback.

3.2.4 Dependent Variable: Mean of Laryngeal Resistance

Results for mean of laryngeal resistance are shown in Tables 18-21 and in Figures 23-29. Findings mirrored those for standard deviation of relative phase. Overall, the performance of the pressed voice quality was produced with increased mean laryngeal resistance as compared to the breathy and normal voice qualities suggesting that the pressed voice quality was produced with more resistance to the flow of air. In addition, mean of laryngeal resistance was increased in the masked auditory feedback condition for all the voice qualities as compared to the normal auditory feedback condition. The performance of the 3 voice coordination patterns, therefore, did vary with feedback. Specifically, the pressed voice quality was produced with increased mean laryngeal resistance in the masked auditory feedback condition, whereas performance of the breathy and the normal voice qualities remained the same across the feedback conditions.

The ANOVA for mean of laryngeal resistance revealed significant main effects for *quality* [$F(1.08,18.43)=15.66$, $p=.001$] and *feedback* [$F(1,17)=10.63$, $p=.005$] and a significant two-way interaction for *quality x feedback* [$F(1.33,22.56)=5.95$, $p=.016$] (see Table 18 and Figures 24, 25, and 26). Neither the main effect for *pitch* [$F(2.42,41.14)=1.16$, $p=.330$] nor the three-way interaction for *quality x pitch x feedback* [$F(2.49,42.48)=.662$, $p=.553$] were significant. Eta squared, an indicator of effect size, was .479 and .385 for the significant main effects of quality and feedback, respectively and .259 for the significant two-way interaction. The significant *quality x feedback* interaction points to a rejection of Ho^{2}. That is, evidence was found for a relationship between voice quality and sensory feedback, relative to mean laryngeal resistance. In contrast, the failure to detect a three-way interaction among the effects of quality, pitch, and feedback on mean laryngeal resistance suggests that no evidence is provided to warrant the rejection of Ho^{1}. Evidence, therefore, was not found for a relationship among voice quality, fundamental frequency, and sensory feedback relative to mean laryngeal resistance.

Within Subjects Effect	SS	df	MS	F	p	Eta²
Quality	4012738.09	1.08	3701976.79	15.66	.001**	.479
Error (quality)	4357419.95	18.43	236468.54			
Pitch	81974.97	2.42	33874.34	1.16	.330	.064
Error (pitch)	1200841.24	41.14	29189.47			
Feedback	150250.33	1.00	150250.33	10.63	.005**	.385
Error (feedback)	240219.48	17.00	14130.56			
Quality x Pitch	245020.67	1.63	150057.95	1.66	.211	.089
Error (quality x pitch)	2513356.26	27.76	90544.36			
Quality x Feedback	172332.45	1.33	129838.43	5.95	.016**	.259
Error (quality x feedback)	492336.69	22.56	21819.74			
Pitch x Feedback	66269.81	2.59	25626.13	.945	.416	.053
Error (pitch x feedback)	1192302.56	43.96	27120.95			
Quality x Pitch x Feedback	82262.01	2.49	32920.13	.662	.553	.038
Error (quality x pitch x feedback)	2110981.84	42.48	49693.30			

N=18

Table 18. Repeated measures ANOVA for quality (i.e., breathy, normal, and pressed), pitch (i.e., increasing fundamental frequency), and feedback (i.e., normal versus masked auditory feedback) on mean of laryngeal resistance. N=18 subjects, SS=sum of squares, df =degrees of freedom considering the Huynh-Feldt correction for sphericity, MS=mean square, F=test statistic, and p=significance level, Eta²=an indicator of effect size. The ** indicates a significant within subjects effect.

Interestingly, the main effects for pitch and all interactions involving pitch were not significant indicating that the subjects were able to maintain the voice qualities regardless of pitch. In Figure 23, the 3 voice qualities were consistently maintained at each of the 7 fundamental frequencies with the highest mean laryngeal resistance for pressed voice and the lowest mean laryngeal resistance for breathy voice.

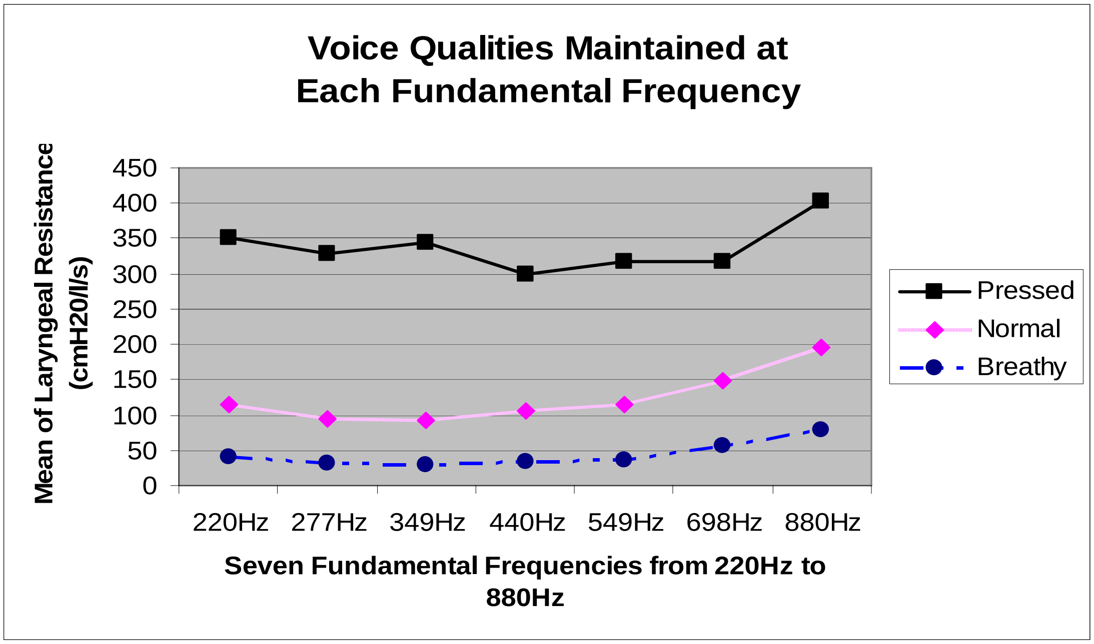

Figure 23. Voice qualities were maintained at each of the 7 fundamental frequencies. Mean of laryngeal resistance (cmH2O/l/s) as a function of fundamental frequency for pressed, normal, and breathy voice qualities.

For the significant main effect of *quality*, the pressed voice quality was produced with the highest mean laryngeal resistance value, whereas the breathy voice quality was produced with the lowest mean laryngeal resistance value (see Figure 24). Consequently, the pressed voice pattern was produced with more resistance to the flow of air presumably due to a constricted glottis as compared to less resistance to the flow of air as seen in breathy voice, presumably due to relative vocal fold abduction.

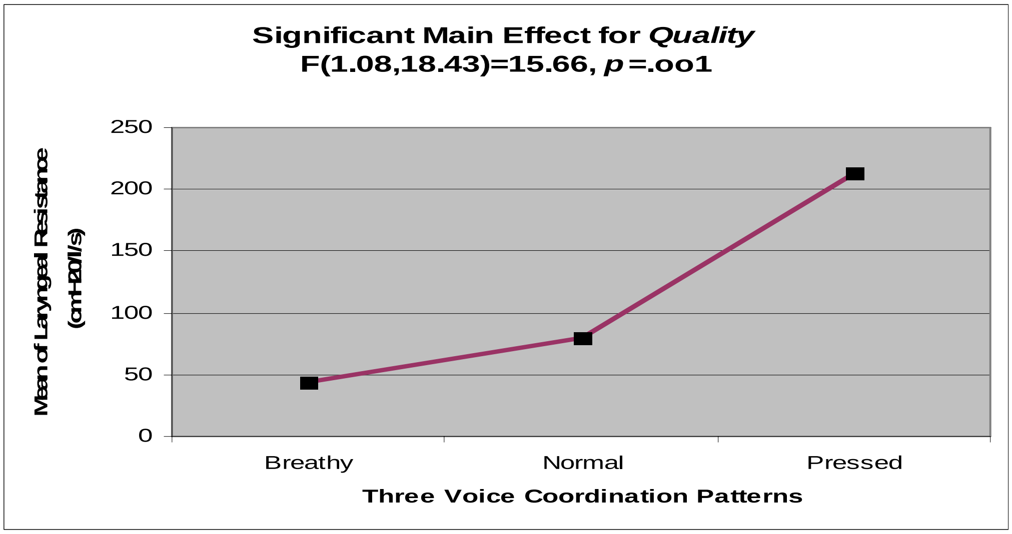

Figure 24. Significant main effect for quality. Mean of laryngeal resistance (cmH20/l/s) as a function of voice coordination pattern (i.e., breathy, normal, and pressed).

Similar to results for standard deviation of laryngeal resistance, subjects produced elevated means values of laryngeal resistance in the masked auditory feedback condition as compared to the normal auditory feedback condition (see Figure 25). Again, this finding implies that in contrast to results for the bimanual coordination task, auditory feedback influenced performance for the voice coordination task.

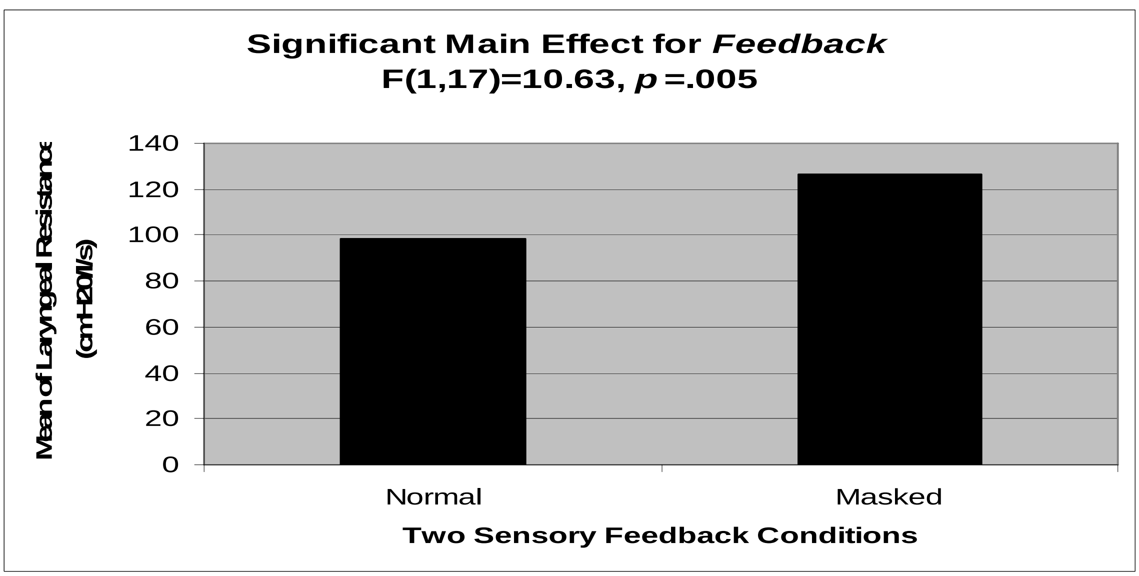

Figure 25. Significant main effect for feedback. Mean of laryngeal resistance (cmH2O/l/s) as a function of sensory feedback (i.e., normal versus masked auditory feedback).

The significant two-way interaction for *quality x feedback* indicated that not only did the masked auditory feedback produce elevated mean laryngeal resistance values, but the influence of the masked auditory feedback condition was dependent upon the specific voice quality. Figure 26 demonstrates that the increase in mean laryngeal resistance was substantially larger for pressed voice in the masked condition, as compared to increases seen in the other voice quality conditions, for which laryngeal resistance increases were trivial.

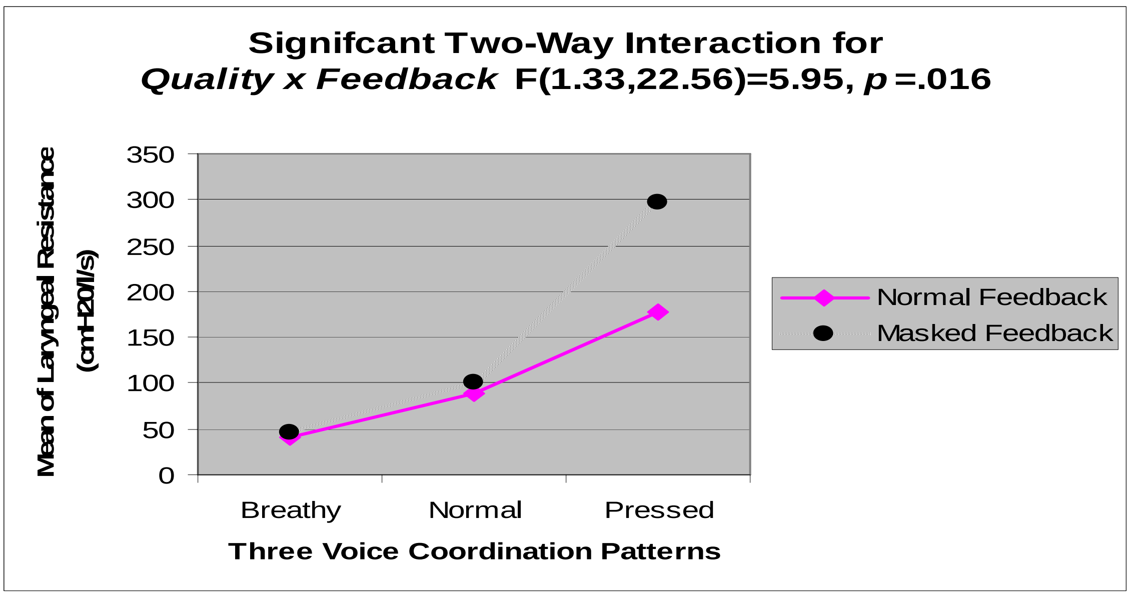

Figure 26. Significant two-way interaction for *quality x feedback*. Mean of laryngeal resistance (cmH2O/l/s) as a function of voice coordination pattern (i.e., breathy, normal, and pressed) for normal and masked auditory feedback.

The significant two-way interaction for *quality x feedback* allowed for further post hoc analysis of simple main effects using the Bonferroni correction, thereby determining the effects of one independent variable while holding the other independent variable constant. For example, determining the effects of the 3 voice patterns (i.e., breathy, normal, and pressed) at a single sensory feedback condition (i.e., normal auditory feedback versus masked auditory feedback by speech noise). Considering the significant two-way interaction for *quality x feedback*, 9 total pairings were tested to compare the 3 voice patterns within a single sensory feedback condition (i.e., 3 voice patterns x 2 sensory feedback conditions = 6) and to compare the 2 sensory feedback conditions within a single voice pattern (i.e., 2 sensory feedback conditions within 3 voice patterns = 3). Because 9 overall tests were performed, the critical p-value was adjusted to account for the 9 tests (.05/9=.005, p-value=.005).

To assess the results for the 3 voice patterns within the normal and masked auditory feedback conditions, 3 pairwise comparisons were conducted: breathy versus normal, breathy versus pressed, and pressed versus normal. For both feedback conditions, all pairwise comparisons were significant (see Tables 19 and 20). Subjects, therefore, maintained distinctions in mean laryngeal resistance values regardless of sensory feedback condition.

Pairwise Comparisons for Normal Auditory Feedback	**df**	**t**	***p***
breathy versus normal	35	3.05	.004**
breathy versus pressed	35	8.55	.000**
pressed versus normal	35	5.49	.000**

Table 19. Pairwise comparisons for normal auditory feedback at breathy, normal, and pressed voice coordination patterns. df=degrees of freedom for the t-distribution, t=test statistic, and p=significance level. The ** indicates a significant pairwise comparison.

Pairwise Comparisons for Masked Auditory Feedback	**df**	**t**	***p***
breathy versus normal	35	3.35	.001**
breathy versus pressed	35	15.66	.000**
pressed versus normal	35	12.31	.000**

Table 20. Pairwise comparisons for masked auditory feedback at breathy, normal, and pressed voice coordination patterns. df=degrees of freedom for the t-distribution, t=test statistic, and p=significance level. The ** indicates a significant pairwise comparison.

To assess results for the 2 sensory feedback conditions within a singe voice pattern, 3 pairwise comparisons were conducted: breathy, normal and pressed (see Table 21). Results showed that laryngeal resistance values were different for normal versus masked conditions, for pressed voice [t(35)=3.51, *p*=.001] (see Table 21). Specifically, pressed voice was produced with larger mean laryngeal resistance values in the masked auditory feedback condition as compared to the normal auditory feedback condition (see Figure 27). In contrast, mean laryngeal resistance values were not different across normal and masked conditions for breathy and normal voice ([t(35)=.177, p=.859] and [t(35)=.318, p=.752], respectively) (see Table 21). Thus, sensory feedback condition did not influence mean laryngeal resistance values for breathy and normal voice qualities (Figures 28 and 29).

Pairwise Comparisons for Feedback within a Single Voice Pattern	**df**	**t**	***p***
normal versus masked feedback at breathy voice	35	.177	.859
normal versus masked feedback at normal voice	35	.318	.752
normal versus masked feedback at pressed voice	35	3.51	.001**

Table 21. Pairwise comparisons for normal and masked feedback within a single voice coordination pattern; breathy, normal, and pressed. df=degrees of freedom for the t-distribution, t=test statistic, and p=significance level. The ** indicates a significant pairwise comparison.

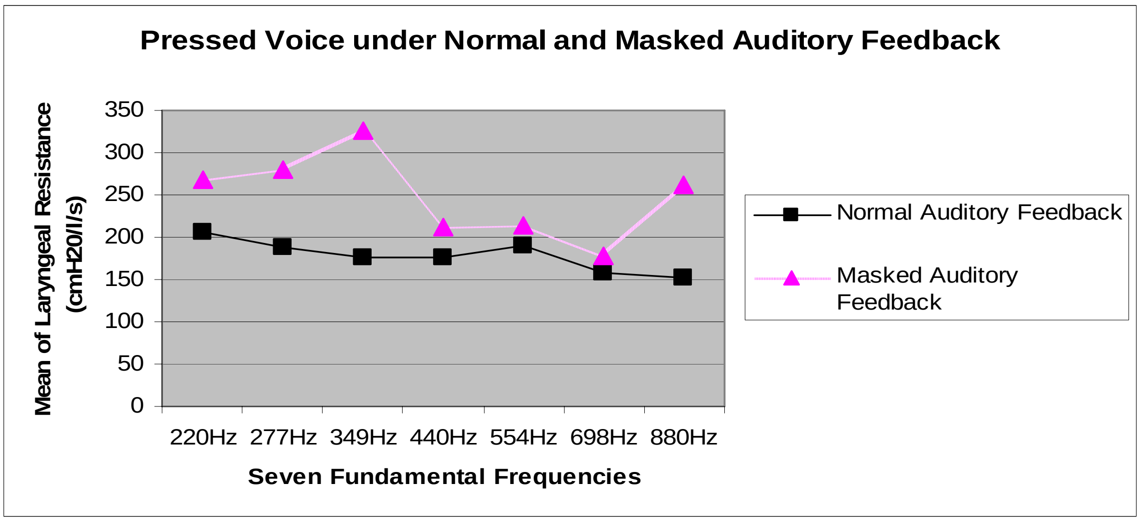

Figure 27. Pressed voice under normal and masked auditory feedback. Mean of laryngeal resistance (cmH2O/l/s) as a function of seven fundamental frequencies (Hz) or pitches for pressed voice under normal and masked auditory feedback.

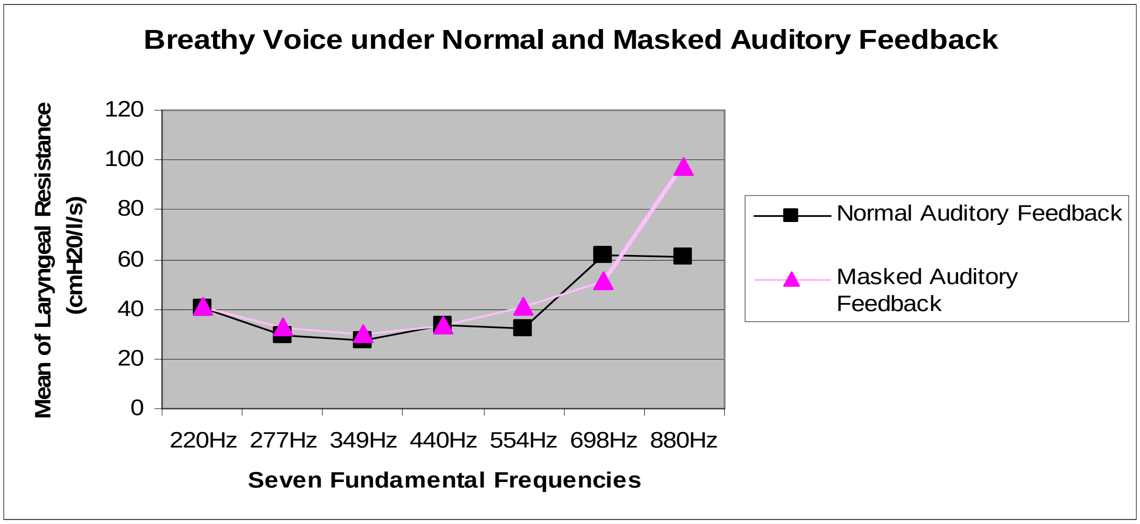

Figure 28. Breathy voice under normal and masked auditory feedback. Mean of laryngeal resistance (cmH2O/l/s) as a function of seven fundamental frequencies (Hz) or pitches for breathy voice under normal and masked auditory feedback.

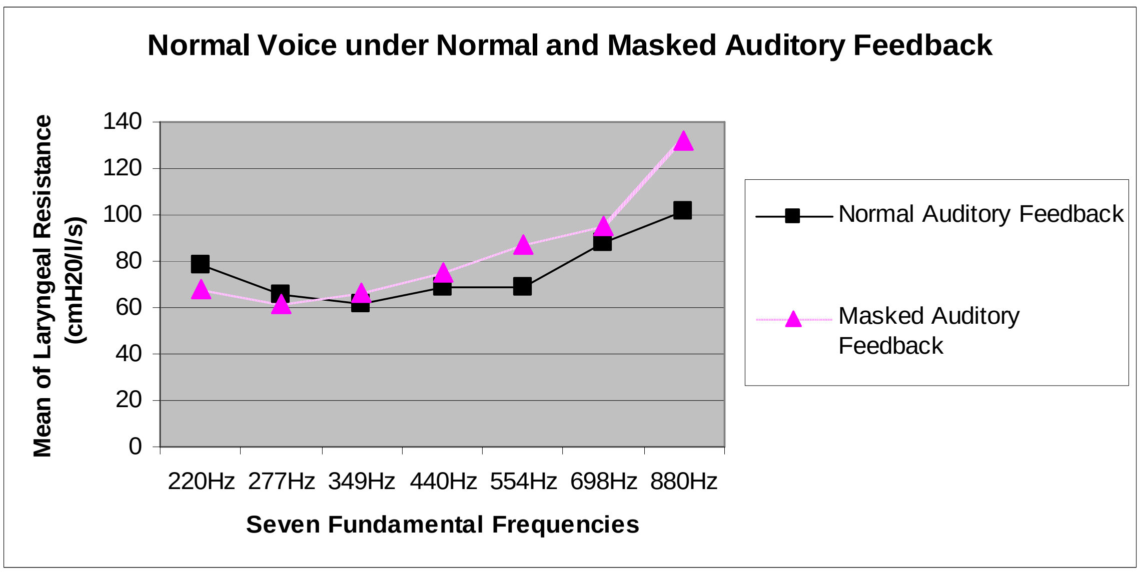

Figure 29. Normal voice under normal and masked auditory feedback. Mean of laryngeal resistance (cmH2O/l/s) as a function of seven fundamental frequencies (Hz) or pitches for normal voice under normal and masked auditory feedback.

3.2.5 Descriptive Analysis of Subjects 17, 19, and 20

Subjects 17, 19, and 20 had characteristics that were very different from the rest of the 18 subjects. For example, subjects 17, 19, and 20 were considered vocal experts with at least 15 years of singing experience in choirs, private voice lessons, and solo singing on the stage;

whereas, the rest of the 18 subjects had at least 3 years of choir singing only. In addition, subjects 17, 19, and 20 had a mean age of 29 years as compared to a mean age of 20 years for the rest of the 18 subjects. The difference in years of training, the type of singing exposure, and the subjects' age appeared to play a substantial role in the outcome of the experiment. To begin with, most of the means and standard deviations of laryngeal resistance for subjects 17, 19, and 20 were extreme outliers when compared to the data for rest of the 18 subjects. In contrast, when subjects 17, 19, and 20 were analyzed for normality without the rest of the 18 subjects, no extreme outliers were noted. Subjects 17, 19, and 20 appeared to form a cohesive group, whereas the remaining 18 subjects appeared to form a different cohesive group. Furthermore, the means and standard deviations of laryngeal resistance for subjects 17, 19, and 20 were higher for all the voice qualities as compared to the rest of the 18 subjects with the pressed voice quality being extremely elevated (see Tables 22 and 23).

Quality & Feedback	**Mean of Laryngeal Resistance** **Subjects 17,19,20 only**	**Mean of Laryngeal Resistance** **All 18 Subjects excluding Subjects 17, 19, 20**
Breathy, Normal	160.16	46.04
Breathy, Masked	121.77	54.47
Normal, Normal	476.72	83.67
Normal, Masked	373.77	91.58
Pressed, Normal	2776.32	194.63
Pressed, Masked	2415.59	327.25

Table 22. Mean of laryngeal resistance (cmH20/l/s) across breathy, normal, and pressed voice qualities under normal and masked auditory feedback conditions for subjects 17, 19, and 20 only and for all 18 subjects excluding subjects 17, 19, and 20.

Quality & Feedback	Standard Deviation of Laryngeal Resistance **Subjects 17,19,20 only**	Standard Deviation of Laryngeal Resistance **All 18 Subjects excluding Subjects 17, 19, 20**
Breathy, Normal	192.17	17.06
Breathy, Masked	101.48	24.01
Normal, Normal	461.98	26.70
Normal, Masked	324.76	31.82
Pressed, Normal	2431.54	67.98
Pressed, Masked	2375.88	178.64

Table 23. Standard deviation of laryngeal resistance (cmH20/l/s) across breathy, normal, and pressed voice qualities under normal and masked auditory feedback conditions for subjects 17, 19, and 20 only and for all 18 subjects excluding subjects 17, 19, and 20.

Not only were the voice qualities produced with higher means and standard deviations of laryngeal resistance in subjects 17, 19, and 20, but the masked auditory feedback condition across all the voice qualities facilitated lower means and standard deviations of laryngeal resistance as compared to the normal auditory feedback condition. In contrast, the rest of the 18 subjects had higher mean and standard deviation values in the masked auditory feedback condition as compared to the normal auditory feedback condition. In addition, for subjects 17, 19, and 20 all 3 voice qualities were produced with the same amount of variability regardless of feedback condition. The shape of graphs in Figures 30, 31, and 32 remained consistent across the normal and masked auditory feedback conditions whereby laryngeal resistance values for the pressed voice quality were the most variable and values for breathy and the normal voice qualities were generally considered less variable. This stands in direct contrast to the results of the 18 subjects. For the 18 subjects, the masked auditory feedback condition caused significantly elevated mean laryngeal resistance values in the performance of the pressed voice quality as compared to the normal auditory feedback condition. The masked auditory feedback condition, therefore, influenced the performance of the pressed voice quality for the 18 subjects, but not for subjects 17, 19, and 20. Interestingly, at the 2 highest pitches, it appeared that subjects 17, 19, and 20 did not maintain the mean laryngeal resistance value of the pressed voice quality. The pressed voice quality appeared to morph into the normal and the breathy voice qualities at 698Hz and 880Hz across both of the sensory feedback conditions (see Figures 33 and 34).

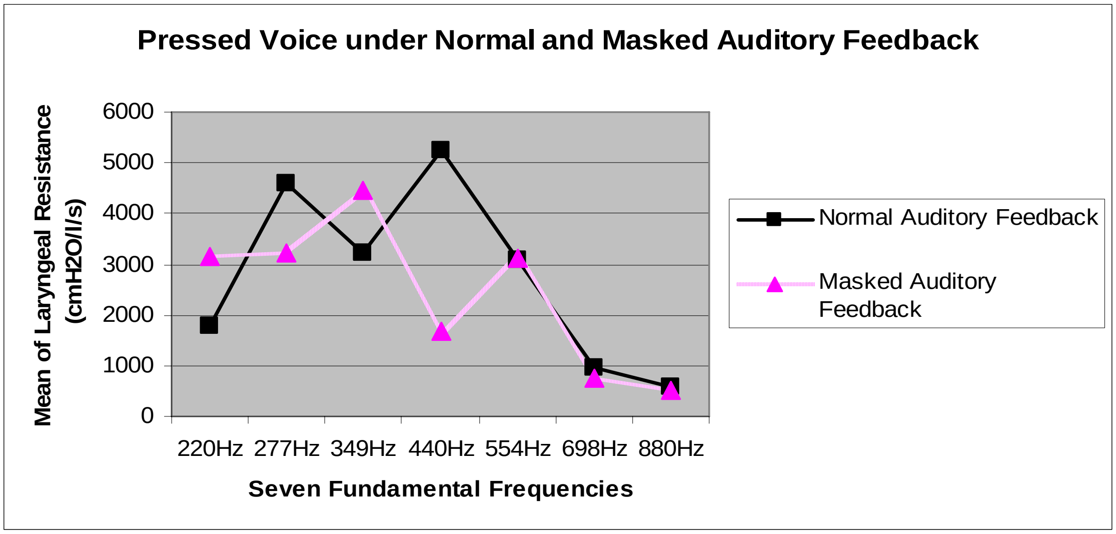

Figure 30. Pressed voice under normal and masked auditor feedback for subjects 17, 19, and 20. Mean of laryngeal resistance (cmH2O/l/s) as a function of the 7 fundamental frequencies (Hz) for normal and masked auditory feedback.

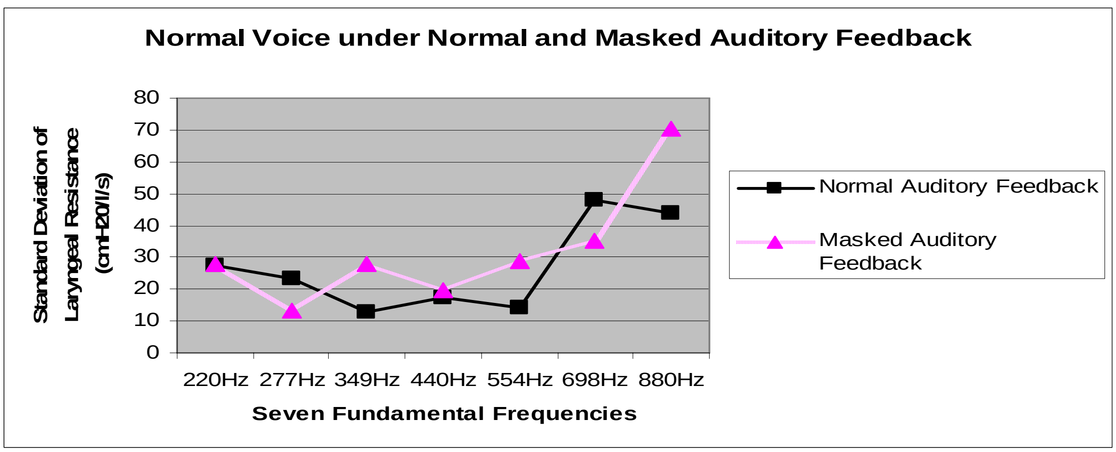

Figure 31. Normal voice under normal and masked auditory feedback for subjects 17, 19, and 20. Mean of laryngeal resistance (cmH2O/l/s) as a function of the 7 fundamental frequencies (Hz) for normal and masked auditory feedback.

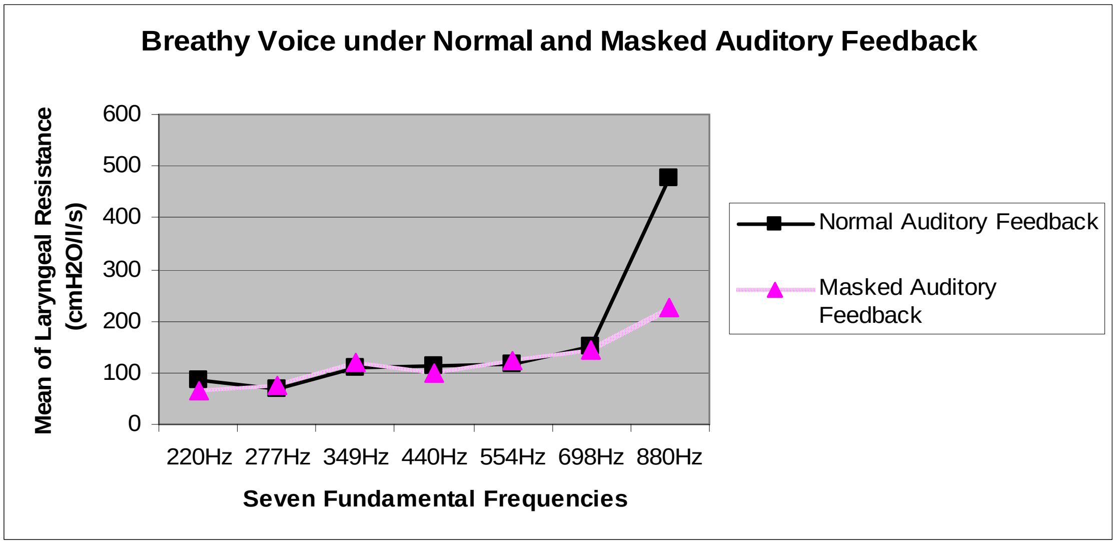

Figure 32. Breathy voice under normal and masked auditory feedback for subjects 17, 19, and 20. Mean of laryngeal resistance (cmH2O/l/s) as a function of the 7 fundamental frequencies (Hz) for normal and masked auditory feedback.

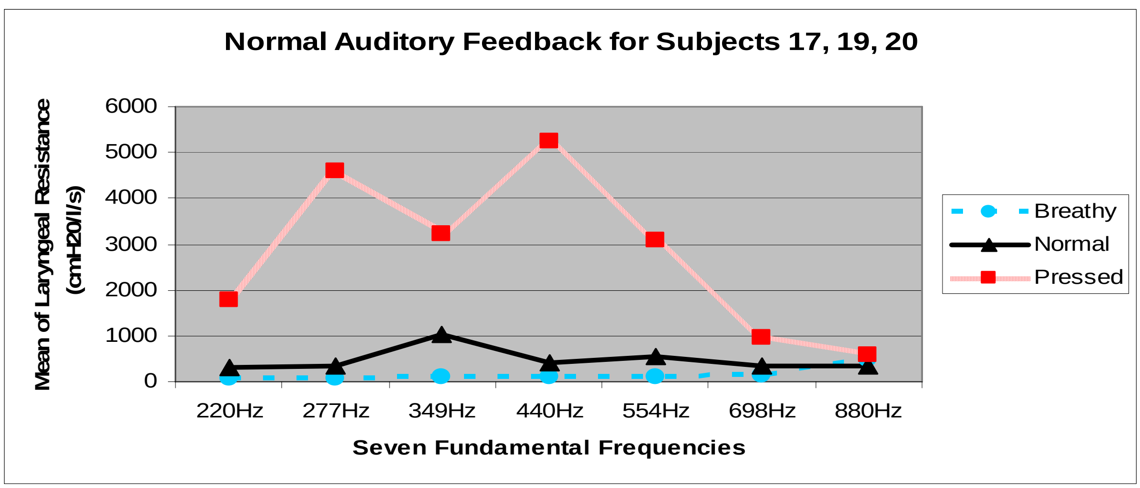

Figure 33. Normal auditory feedback for subjects 17, 19, 20 across breathy, normal, and pressed voice qualities. Mean of laryngeal resistance (cmH2O/l/s) as a function of the 7 fundamental frequencies (Hz) for breathy, normal, and pressed voice qualities.

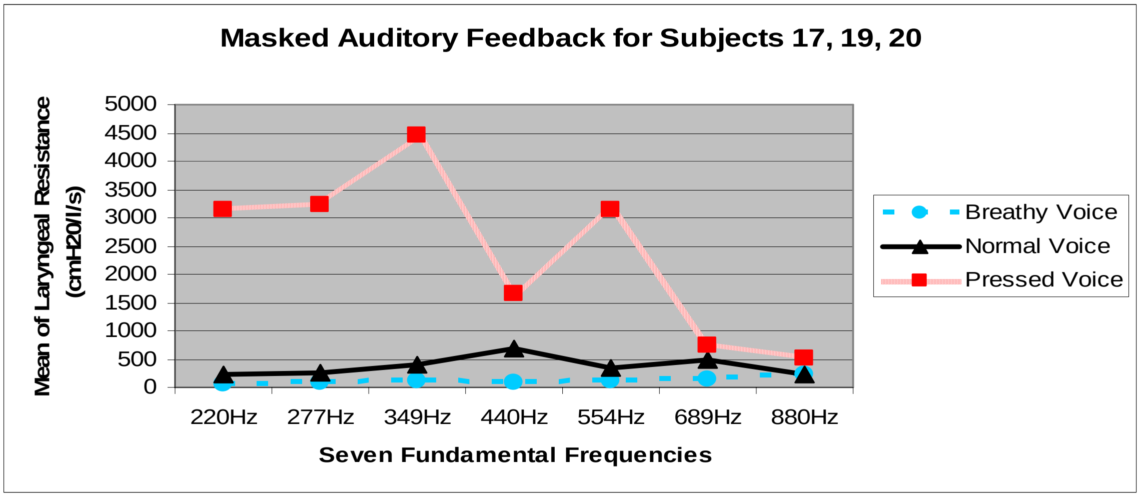

Figure 34. Masked auditory feedback for subjects 17, 19, 20 across breathy, normal, and pressed voice qualities. Mean of laryngeal resistance (cmH2O/l/s) as a function of the 7 fundamental frequencies (Hz) for breathy, normal, and pressed voice qualities.

In summary, "expert" subjects 17, 19, and 20 performed differently from the rest of the 18 subjects. Overall mean and standard deviations of laryngeal resistance were higher for subjects 17, 19, and 20 as compared to the other 18 subjects. The masked auditory feedback condition facilitated a general decrease in mean and standard deviations as compared to the normal auditory feedback condition for subjects 17, 19, and 20. In contrast, the rest of the 18 subjects had an opposite effect of performance where the masked auditory feedback condition facilitated an increase in means and standard deviations of laryngeal resistance. The feedback conditions did not appear to influence the performance of 3 voice coordination patterns in subjects 17, 19, and 20; however, the masked auditory feedback condition did significantly influence the performance of the pressed voice quality in the rest of the 18 subjects. In addition, subjects 17, 19, and 20 failed to maintain the mean laryngeal resistance value reflecting pressed voice at 698Hz and 880Hz, whereas, the rest of the 18 subjects were able to maintain laryngeal resistance values reflecting all the voice qualities across the fundamental frequency range. The difference in performance between "expert" subjects 17, 19, and 20 and the rest of the "less-than-expert" 18 subjects may be related to different subject characteristics involving years of vocal training, type of vocal training, performance history, and age.

3.3 DISCUSSION

The purpose of Experiment 2 was to investigate the effect of sensory feedback conditions, voice quality, and increasing fundamental frequency on mean and standard deviation of laryngeal resistance. A central theoretical construct in the investigation regarded the role of sensory information in the coordination dynamics for a voice task. Examination of the data indicated that data for three of the total 21 subjects were qualitatively different from data for the remaining 18 subjects, based on descriptive stem and leaf plots indicating extreme outliers. Statistical consideration involved the data set from the 18 subjects, which will be the focus of the present discussion. Data for the three remaining subjects were considered descriptively and will be discussed later on in the discussion section.

Results showed that both voice quality and feedback condition influenced the stability of the laryngeal resistance data. Relative to voice quality, subjects produced pressed voice with the greatest variability, whereas breathy voice was produced with the least variability. Variability for normal voice landed in the middle, but was closest to the variability for breathy voice. The pressed voice quality appeared to have an inherent instability as compared to the breathy and the normal voice qualities. The increased variability of the pressed voice quality may be explained by the heightened muscle activation of the constricted glottis enabling a highly variable relationship between the airflow through the glottis and the build up of air below the glottis. In contrast, the relative stability of the normal voice quality, produced with an average muscle activation enabling a neutral glottis, promoted a stable and balanced relationship between the airflow through the glottis and the build up of air below the glottis. For the breathy voice quality, the most stable relationship occurred between airflow through the glottis and build up of air below the glottis possibly due to the minimal muscle activation of the abducted glottis. In sum, as muscle activation increases toward heightened glottal constriction, the relationship between airflow through the glottis and build up of air below the glottis becomes more variable. Conversely, as muscle activation decreases toward minimal glottal constriction or an abducted glottis, the relationship between airflow through the glottis and build up of air below the glottis becomes less variable.

Relative to the effect of feedback on the stability of laryngeal resistance measures for the 18 subjects, the standard deviation of laryngeal resistance increased under masked listening conditions. That is, when auditory feedback about subjects' performance was effectively eliminated, variability in laryngeal resistance values for the voice qualities increased significantly. In contrast to findings for the bimanual limb coordination task, sensory feedback was found to influence dynamic coordinative behavior for a voice task. This finding is loosely consistent with prior reports indicating a relevance of sensory information for coordinative motor behavior (Cardoso de Oliveira & Barthelemy, 2005; Kazennikov et al., 2002; Mechsner et al., 2001, 2004; Serrien & Teasdale, 1996; Swinnen et al., 2000). Considering an expanded view of dynamics systems theory including the influence of auditory feedback in the coordination dynamics of a voice task, the rationale for including the auditory feedback component in the candidate's developing *Global Voice Therapy Program* is supported by the current theoretical investigation (Grillo, in preparation).

Although there are potential implications for dynamic systems theory of motor control, in fact, evidence supporting a role of sensory feedback on motor control fits squarely with most other theoretical approaches to motor control and learning. Examples include a closed-loop theory of motor control (Adams, 1971) and schema theory (Schmidt, 1975, 1976, 2003). Based on such theories (Adams, 1971; Schmidt, 1975, 1976, 2003) supporting a role of sensory feedback, the finding that auditory feedback played a role in motor control for a voice task is not surprising at all. Further evidence regarding such a role of sensory feedback comes from data on speech deterioration in individuals with post-lingual onset of deafness, which typically appear after a period of some years (Anderson & Lyxell, 1998; Lane & Webster, 1991).

Regarding measures of average laryngeal resistance, two significant main effects and one two-way significant interaction were demonstrated in the data. Specifically, voice quality, feedback condition, and the interaction of voice quality and feedback influenced average laryngeal resistance. Addressing these findings in turn, pressed voice was produced with the highest average laryngeal resistance, whereas breathy voice quality was produced with the lowest average laryngeal resistance. Average laryngeal resistance was intermediate for normal quality, but was closer to values for breathy than for pressed voice. These findings are consistent with those that would be predicted for the respective voice qualities. Pressed voice is typically produced with a small glottis, which would limit airflow through the glottis and cause a corresponding back-up of pressure in the trachea (i.e., subglottis). Thus, laryngeal resistance, which reflects subglottic pressure divided by glottal airflow, should be high. In contrast, breathy voice is typically produced with a relatively wide glottis. Thus, phonatory airflow through the glottis should be high and pressure back-up in the subglottis should be comparatively low. The result would be low values for laryngeal resistance. Values for normal voice should be intermediate due to an intermediate glottal size and thus intermediate glottal airflows and subglottal pressures (e.g., , Gauffin & Sundberg, 1989). The mean laryngeal resistance values in the current study, therefore, were consistent with aerodynamic and laryngeal properties of the specific voice quality.

Conceptually more interesting are findings for mean laryngeal resistance as a function of feedback condition. Across both the normal and masked auditory feedback conditions, the mean laryngeal resistance was significantly different for all the voice qualities. All 3 voice qualities as they relate to one another, therefore, were maintained regardless of changing auditory feedback. Even though all 3 voice qualities were distinct from one another within each sensory feedback condition, the pressed voice quality was produced with significantly higher mean laryngeal resistance in the masked auditory feedback condition as compared to the normal auditory feedback condition. The breathy and the normal voice qualities were produced with the same mean laryngeal resistance across the normal and masked auditory feedback conditions. The inherent stability of the breathy and normal voice qualities was not affected by the feedback conditions. In contrast, the performance of the pressed voice quality was affected by the masked auditory feedback condition. That is, the mean laryngeal resistance for the pressed voice quality increased in the masked auditory feedback condition as compared to the normal auditory feedback condition.

Although constant intensity levels were encouraged across all trials, in fact subjects failed to achieve the target intensity level (i.e., +/-1dB from a "comfortable" intensity). Thus, the results may reflect subjects' tendency to increase intensity under masking (e.g., "Lombard effect"), but not to increase laryngeal resistance. All 3 voice qualities had an increase in intensity level in the masked condition. Interestingly, the normal voice was produced with the highest intensity levels in the masked auditory feedback condition as compared to breathy and pressed voice. If average laryngeal resistance was affected by the increased intensity in the masked condition, then the average laryngeal resistance values for the normal voice quality would have been affected. This was not the case. In fact, the breathy and the normal voice qualities were performed with the same average laryngeal resistance across both the normal and masked auditory feedback conditions, even though intensity levels were higher in the masked condition. Conversely, the pressed voice quality was performed with elevated average laryngeal resistance values in the masked auditory feedback condition. The increase in intensity under masking, therefore, did not influence laryngeal resistance.

The main point to pursue for theoretical purposes is that pressed voice quality was produced with significantly higher mean laryngeal resistance values under masking, but values for breathy and normal voice did not vary across normal and masked feedback conditions. The implication is that sensory feedback is necessary for some but not all laryngeal resistance targets. That is, sensory feedback appeared largely relevant for the pressed voice condition but not for breathy and normal voice conditions. Together with the observation that pressed voice was less stable than breathy and normal voice qualities, the implication is that *sensory feedback may be relevant for voice patterns that have a shallow basin of attraction (i.e., pressed), but less relevant or even wholly irrelevant for voice patterns that have a steep basin of attraction (i.e., breathy and normal).*

Stated in theoretical terms pertinent to dynamic systems theory, perhaps the steep basins of attraction for breathy and normal voice qualities were driven by coordination dynamics, whereas the shallow basin of attraction for pressed voice production was at least partly influenced by auditory feedback processes. Evidence from the present study of a role of both coordinative dynamics, as seen in breathy voice and normal voice, and sensory feedback processes, as seen in pressed voice, suggests that further theorizing in motor control should seek to handle both coordinative dynamics and sensory feedback. The influence of auditory feedback on a voice coordination task also supports the importance of auditory feedback in vocal rehabilitation.

3.3.1 Subjects 17, 19, and 20

Subjects 17, 19, and 20 had different personal and performance characteristics from the rest of the subjects. Subjects 17, 19, and 20 (mean age 29 years) had 15 or more years of singing experience that included private classical vocal training, choral singing, and solo singing on the stage, which labeled them as "expert" subjects. The rest of the subjects (mean age 20 years) had a history of at least 3 years of choral singing only. This difference in type of training, years of training, and age appeared to promote a different outcome in performance for the subset of "experts" in comparison to other subjects. For example, all the voice qualities were produced with increased laryngeal resistance to the flow of air and with increased variability in the "expert" group as compared to the other subjects. It was almost as if subjects 17, 19, and 20 produced extreme exemplars of each of the voice qualities. Moreover, both means and standard deviations of laryngeal resistance decreased slightly in the masked auditory feedback condition as compared to the normal feedback condition in the "expert" group. The other 18 subjects had the opposite effect with the means and standard deviations of laryngeal resistance slightly increased in the masked auditory feedback condition as compared to the normal auditory feedback condition.

Additionally, the performance of the voice qualities for the "expert" subjects did not appear to be influenced by the auditory feedback conditions, whereas the performance of the pressed voice quality in the other subjects was affected by the masked auditory feedback condition. One obvious explanation is that the "expert" subjects relied more on proprioceptive feedback rather than auditory feedback to maintain the breathy, normal, and pressed voice qualities. This is a plausible explanation and should be pursued with further study. At high pitches greater than 698Hz, the coordination dynamics for the pressed voice quality were not maintained in the "expert" subjects. Perhaps through extensive vocal training, voice teachers and coaches emphasized the importance of maintaining an open and relaxed larynx especially at high pitches above 698Hz. The pressed voice quality at 698Hz and 880Hz went against the teaching of voice teachers and coaches and therefore, the "expert" subjects morphed the pressed voice quality into breathy and normal voice qualities at the 2 highest pitches.

The difference in performance outcome between the 3 subjects with extensive vocal training and the 18 subjects with minimal vocal training presents an interesting qualifier to interpretation of results from the current study. That is, not only sensory information, but also years and type of vocal training appeared to play a role in the coordination dynamics of a voice task. The use of auditory and perhaps proprioceptive feedback on the coordination dynamics of a voice task, therefore, may also be related to the level and type of vocal expertise of the performer.

3.3.2 Limitations

A limitation of the study involved a perceptual goal of voice quality measured by laryngeal resistance rather than a numeric standard of laryngeal resistance measured by laryngeal resistance. Although laryngeal resistance is a valid measure of breathy, normal, and pressed voice qualities (Grillo & Verodlini, in preparation), a 1:1 relationship does not exist. In Experiment 1, the goal was a numeric standard of relative phase and performance was measured by relative phase. In an effort to extend investigation beyond the typical bimanual domain, it was determined that at this early stage on investigation perceptual goals would better reflect the coordination dynamic of a voice task rather than numeric standards. Future investigation should determine if numeric standards of laryngeal resistance are feasible. If the numeric standards are feasible, then investigation should attempt to compare results across a numeric goal of laryngeal resistance versus a perceptual goal of voice quality.

A second limitation of the study involved the subject characteristic of years and type of vocal training. An inclusion criterion of at least 3 years of choral singing experience was set for subject enrollment with no limit on type and years of vocal training. This lack of control for subject characteristics facilitated the performance differences between the 3 subjects with extensive vocal expertise and the 18 subjects with comparatively minimal vocal expertise. Data for 18 out of the total 21 subjects were used in data analysis. A close to significant 2-way interaction between quality and feedback was demonstrated for standard deviation of laryngeal resistance ($p=.072$). The findings for the quality and feedback interaction on standard deviation of laryngeal resistance appeared to be consistent with findings from the significant 2-way interaction for quality and feedback on mean of laryngeal resistance. Perhaps the loss of power by excluding the 3 "expert" subjects influenced the non-significant finding for the quality and feedback interaction on standard deviation of laryngeal resistance.

A third limitation concerns the ability to generalize the findings to other populations and other tasks within the voice domain and beyond. As noted, the subject pool consisted of young, trained adult female singers. Thus, results cannot be easily generalized to children, adult males, elderly females, or non-singers. The findings that were obtained appeared rather robust and should be generalizable to the population of females (average age of 20 years) with three or more years of choral singing experience only.

4.0 CHAPTER 4: CONCLUSIONS AND AVENUES FOR FUTURE RESEARCH

Experiment 1 assessed performance on a bimanual coordination task for a 0º in-phase and a 180º anti-phase coordination pattern at slow (1 Hz), medium (2 Hz), and fast (3 Hz) speeds under different conditions of visual and auditory feedback. Results showed that increasing speed of bimanual oscillations deteriorated performance for the 180º anti-phase pattern, but did not affect the 0º in-phase pattern. The continuous stability of the 0º in-phase pattern at increasing speeds, the mutual stability of both the 0º in-phase and the 180º anti-phase patterns at the slow speed, and the destabilization of the 180º anti-phase pattern at increasing speeds represents a replication of findings previously reported in the literature (Kelso, 1984; Scholz & Kelso, 1989, 1990; Tuller & Kelso, 1989).

In contrast, previous findings of a relevance of sensory information for performance on a bimanual coordination task (Cardoso de Oliveira & Barthelemy, 2005; Kazennikov et al., 2002; Mechsner et al., 2001, 2004; Serrien & Teasdale, 1996; Swinnen et al., 2000) were not replicated in Experiment 1. In Experiment 1, performance stability was not affected by either visual or auditory feedback pertinent to the bimanual coordination task. In difference to that finding, Experiment 2, which assessed performance on a voice coordination task, showed that sensory feedback was relevant to task performance. Auditory deprivation produced an increase in variability and an increase in mean laryngeal resistance under masking as compared to normal feedback conditions, for minimally trained adult female vocalists. Specifically, pressed voice quality was produced with increased mean laryngeal resistance in the masked auditory feedback condition as compared to the normal auditory feedback condition, whereas resistance values remained constant for breathy and normal voice qualities across feedback conditions. The pressed voice quality may be more susceptible to auditory feedback influence because it was more variable than the breathy and the normal voice qualities. Thus, sensory processes were relevant to performance for some but not all of the voice tasks.

A question regards the difference in results across the studies. In order for results to contribute to theoretical developments pertinent to motor control, consistent results should be seen across domains. In the present study, findings regarding the relevance of sensory feedback for motor control were inconsistent as a function of task domain; limb versus voice. As noted, evidence of a role for feedback was not obtained for the limb task, but was seen for the voice task. Several possible explanations can be conceived. First, perhaps a difference in task domain affected the results. The limb study dealt with a physical movement having little applicability to everyday use, whereas the voice study appealed to a system that is used daily for communication.

Second, perhaps the difference in results was related to the requirements of the specific task, more than to task domain. Perhaps bimanual coordination is shaped at least as much by proprioception as it is by vision (or audition). Proprioception was not controlled in the present study. Thus, feedback may indeed be relevant for the limb task, but the task-appropriate type of feedback was not modulated in the study.

Third, perhaps a difference in subject type played a role in the results. In the limb study, novices were enrolled who had no prior experience with the bimanual coordination task. In the voice study, experienced vocalists were enrolled. Thus, it is conceivable that experience plays a role in the relevance of sensory feedback for motor control. Some evidence consistent with that possibility was seen in the voice experiment. Subjects with greater vocal experience and presumably more expertise did not show much of an influence of auditory feedback on motor control, whereas subjects with relatively less experience did show an influence.

Fourth, a more interesting hypothesis again has to do with the potential relevance of task specificity for the results, but in a different direction than the one already introduced. In Experiment 2, sensory feedback was shown to be pertinent for a voice coordination task that appeared generally unstable (i.e., pressed voice), but not for tasks that were inherently more stable (i.e., breathy and normal voice). Although the 180º pattern was shown to be less stable than the 0º pattern for the limb task, perhaps the 180º pattern was not sufficiently unstable for a role of sensory feedback to emerge. This possibility is an interesting one that would be of particular interest to pursue with further, appropriately designed studies.

Another discrepancy in findings across the study was the role of "frequency of oscillation" for task performance. Frequency played a clear role for performance accuracy in the limb study, but did not play any discernible role for results in the voice study. In the limb study, frequency was regulated by the striated, voluntary muscle system. In the voice study, frequency was largely regulated by passive aerodynamic, myoelastic features of vocal fold tissue once the laryngeal system achieved a stable posture (Titze, 1980). This difference in motor control for frequency changes across the limb and the voice tasks may explain the discrepancy in findings.

In the meantime, it is interesting to consider how the results relate to existing theories of motor control, and what theoretical adjustments, if any might be required to accommodate the results. The results of the voice study showed that sensory feedback may be relevant for voice patterns with a shallow basin of attraction, but irrelevant for voice patterns with a steep basin of attraction. From the prospective of schema theory (Schmidt, 1975, 1976, 2003), the more stable voice patterns may be governed by feedforward mechanisms specified by a recall schema, whereas the less stable voice pattern may be influenced by the activation of the recognition schema in the evaluation of sensory feedback. From the prospective of dynamic systems theory and the original HKB (1985) model, the more stable voice patterns (i.e., breathy and normal) were governed by coordinative dynamics. The change in performance of the pressed voice quality across feedback conditions cannot be explained by coordinative dynamics alone. Sensory feedback connections influenced the performance of the coordination dynamics for the pressed voice quality. What is needed, therefore, is an expanded view of dynamic systems theory that considers sensory feedback influences on coordinative dynamics.

Investigation should continue around this expanded view of dynamic systems theory in an effort to generalize findings across 2 or more movement domains; such as a limb and a voice task. To limit the differences between a limb and a voice task, future research should focus on the identification of all sensory feedback conditions that influence the demands of a limb and a voice task. In a limb task involving the bimanual linear slide, visual, auditory, and proprioceptive feedback should be controlled. In a voice task involving aerodynamic measures, auditory and proprioceptive feedback should be controlled. Future research should also focus on the identification of similar movement goals between a limb and a voice task that require the same level of expertise. For example, to be consistent with the goal of the voice study, the goal of the limb study should include a level of expertise as seen in touch typing skills or piano playing. Finding a way to merge bimanual coordination dynamics with voice coordination dynamics in one ultimate movement and communication goal may also be an option for improving generalization of findings across the 2 domains.

Turning to practical considerations, the question arises about the potential applicability of the results for clinical or other physical training practice. If the findings from the present series are real, the implication is that physical training programs should emphasize sensory feedback processes, perhaps more than is commonly considered in practice. In fact, a newly developing *Global Voice Therapy Program* emphasizes the relevance of both auditory and kinesthetic feedback for the performance of newly learned behaviors, and also for generalization and maintenance of those behaviors (Grillo, in preparation). Once developed, such models should be subjected to the scrutiny of evaluation in the field, to determine the relevance of sensory factors in training at the applied level.

In sum, the current studies provide further impetus for continued research regarding the role of sensory feedback influences in the coordination dynamics of limb, voice, and other tasks. Facilitation of the basic knowledge regarding greater advances in the understanding of how sensory feedback and motor mechanisms interact in adaptive, biological systems is critical to the development of physical training and rehabilitation programs and an emerging theoretical framework founded in a heterarchical perspective with consideration of sensory feedback influences on coordinative dynamics. With continued investigations, physical therapists, occupational therapists, speech-language pathologists, voice therapists, and other rehabilitation specialists, as well as athletic trainers will hopefully be more equipped to base assessment and treatment plans on theoretical investigations exploring the intersection of sensory feedback and motor mechanisms.

5.0 CHAPTER 5: BIBLIOGRAPHY

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