THE ROLE OF FEEDBACK AND AGE-RELATED DIFFERENCES IN FORCE PRODUCTION ACCURACY, VARIABILITY, AND SHAPE ACROSS ORAL AND MANUAL EFFECTORS

BY

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DISSERTATION

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ABSTRACT

The purpose of this dissertation was two-fold: 1) to determine the role of feedback in force production accuracy, variability, and shape and 2) to determine whether sensory feedback mediates age-related difference in force production accuracy, variability, and shape across effectors. The premise of these experiments was that the type of sensory feedback would influence discrete force production. In order to test this premise, two experiments were conducted. Experiment 1 involved 72 college-aged participants (mean=23.4 years old, SD=4.22) randomly assigned to one of four groups (a no feedback, grayscale, auditory, and visual feedback condition). Sensory feedback was equated by determining one’s average ability to discriminate different feedback modalities (i.e., auditory, grayscale, and visual feedback). Participants produced isometric force via elbow flexion to match a Gaussian template waveform with a peak force of 90 N and a time to peak force at 200 ms. Each participant completed 90 trials. Force production accuracy and shape was indexed for each trial. Force production accuracy was assessed with absolute error (AE) of peak force, time to peak force, and mean squared error. Absolute error of peak force was computed by taking the absolute value of the actual peak force minus the criterion peak force (i.e., 90 N). Absolute error of time to peak force was computed by taking the absolute value of the actual time to peak force minus the criterion time to peak force (i.e., 200 ms). Mean squared error (MSE) was computed by taking the summation of squares of the criterion trajectory minus actual trajectory then dividing this value by the number of points. Force variability was assessed using the standard deviation (SD) and coefficient of variation (CV) of impulse, peak force, time to peak force, and peak rate of force production. Force pulse shape was assessed with mean skewness, mean kurtosis and the mean, standard deviation (SD), and coefficient of variation (CV) of the inflection point of a logistic fit. Inflection point is the midpoint of the logistic curve. Results from Experiment 1 indicated feedback influenced AE of
peak force, MSE, CV of peak force and time to peak force, skewness, kurtosis, inflection point, and curve length. The type of feedback was found to influence temporal measures. The force shape analysis revealed auditory, grayscale and visual feedback resulted in more symmetric force pulse shapes than without feedback. In Experiment 2, 12 young (mean=23.5±3.3 years) and 11 old (mean=73.2±6 years) produced isometric force with auditory or visual feedback via elbow flexion or jaw elevation to a Gaussian waveform template. The Gaussian waveform template had a peak of 50 N and a time to peak of 200 ms. Each participant performed 70 trials and the last 40 trials were used for analysis. The same dependent variables used in Experiment 1 were used in Experiment 2. Results indicated effector x feedback interactions on force production accuracy and SD of impulse. Results indicated age x feedback interactions on CV of peak force, age x effector interaction on skewness, and age x effector x feedback interaction on SD of peak rate. The force shape analysis revealed the jaw produces more non-symmetric impulses than the elbow. Older adults had difficulty producing a symmetric force-pulse in the elbow in comparison to younger adults. Taken together, results from Experiment 2 indicate that feedback is fundamental to the motor command and age-related differences in force variability depend on the type of feedback and effector.
To my late half-sister Gertrude Ofori
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CHAPTER 1
INTRODUCTION

Sensory information plays a vital role in movement control. Consider the complex task of playing a score of music on a piano and singing. A person visually interprets the notes and words on the paper and produces audible sounds with the piano while synchronizing his or her mouth to convey to the audience the notes and words of the song. In this complex task, the musician coordinates varied information from multiple senses to produce motor responses that create a certain perception to the audience. Visual feedback from the fingers, auditory feedback from the notes played, and tactile feedback from the fingers and lips may be used to coordinate the proper actions. While the role of sensory feedback in movement control has been a topic of research for over a century (Woodworth, 1899), there has been little research examining the role of auditory feedback for movement control. Recent comparisons between visual and auditory feedback in movement tasks have suggested that visual feedback facilitates accuracy in spatial aspects of a task while auditory feedback facilitates temporal accuracy (Coull, Tremblay, Elliott, 2001; Guttman, Gilroy, & Black; 2005; Ofori, Loucks, & Sosnoff, 2012). However, there is a dearth of information concerning the role visual and auditory feedback play in facilitating accurate force control over trials.

The ability to regulate force is essential for accurate movement. One way to assess accuracy is to examine variability of motor output when trying to produce the same action over several trials. The study of force variability has been approached from two distinct paradigms: discrete and continuous force production. In discrete force control tasks individuals must adapt force impulses to specific force levels and timing characteristics with extrinsic sensory feedback about performance usually being provided post-trial. Open-loop commands generally
predominate. In continuous force control tasks individuals must maintain a required force for a longer duration and extrinsic sensory feedback about performance is usually provided within the trial. Closed-loop control processes are suggested to predominate. Clearly distinct control processes operate in discrete force control tasks and continuous force control tasks (Ofori, Sosnoff, Carlton, 2012); however, the influence of a particular mode of sensory feedback in the regulation of force in either force control task is unclear. Discrete force control tasks have a temporal component that must be regulated; whereas, continuous force control tasks have minimal temporal regulation. Auditory feedback may be more beneficial than visual feedback for providing extrinsic feedback for discrete force control tasks. Because auditory feedback has shorter feedback loop time in comparison to visual feedback, auditory feedback may also facilitate accuracy in continuous force control tasks.

For over a century, reports have shown that response produced feedback provides clear benefits for precision tasks either in the form of online feedback (Woodworth, 1899) or post response knowledge of results (Trowbridge & Cason, 1932). The contribution of sensory feedback to force variability and accuracy in discrete and continuous force control tasks is unclear. Many reports indicate that providing online visual feedback during the task in continuous force control tasks results in greater performance accuracy (e.g., Vaillancourt & Russell, 2002). The contribution of visual feedback to force variability has revealed conflicting findings. For example, Tracy (2007) reported that visual feedback increased force variability during continuous force production in the ankle. In contrast Sosnoff & Newell (2008) have shown that removal of visual feedback causes increases in force variability. Thus, it is unclear how and why sensory feedback affects variability in continuous force control tasks. One variable that may contribute to these different findings is the use of detrending. Detrending is a
procedure that removes the change in the mean force output over time. While this procedure may be advantageous for examining stationary characteristics of a dynamic system, this procedure may influence spectral properties of the force output that provide distinct information independent of the traditional measures of force variability (e.g., standard deviation) (Slifkin & Newell, 1999).

In discrete force control tasks, force pulses are usually short in duration such that online sensory feedback may have minimal use during force production; however, feedback may serve to reduce error on forthcoming trials. There have not been any reports to our knowledge that have provided online visual feedback about task performance during discrete force control tasks where the time to peak force criterion is less than 200 ms. However, there have been reports examining the influence of visual feedback in discrete tasks where the time to peak force criterion was longer (i.e., > 300 ms). Ranganathan & Newell (2009) found that online visual feedback decreased force variability in comparison to no online visual feedback. The time to peak force in their experiment was 600 ms. There is no evidence that online visual feedback enhances accuracy or reduces variability over post-trial feedback when the time to peak force is shorter than visual processing time (e.g., ≤ 135 ms). Additionally, it is unknown how other sensory modalities influence the relation of feedback to force variability.

The rate of force production or time to peak force has been shown to be a critical variable to control in discrete force control tasks. If timing is a key control variable, auditory feedback may be more advantageous than visual feedback. Auditory feedback has been suggested to provide more information concerning the timing of the task (Ayetkin et al., 2008). If indeed auditory feedback can elicit more time sensitive information concerning task performance, sensory modalities may differ in their facilitation of accurate force control.
Exteroceptive sensory information is linked to exteroceptive receptors such as the eyes and ears and provides information about the spatial representation of the task. This information is critical for movement planning, updating the motor command, providing information about the force trajectory, and information about task performance. Somatosensory and proprioception information, on the other hand, provides information regarding the state and configuration of the body and movement dynamics. This information is linked to receptors, such as tactile, vestibular receptors, and Golgi tendon organs. This information is critical for knowing relative position of the limbs, forces acting on the body, and an internal sense of movement.

The classification of sensory information as extrinsic or intrinsic may also be important for force regulation. Intrinsic information is inherent to the action and includes proprioceptive, visual, auditory, tactile signals usually termed “response-produced feedback”. Extrinsic information, on the other hand, is information provided from an external source and is supplemental to intrinsic signals. Extrinsic information can be provided in a variety of ways; such as during, immediately following, or delayed in time with respect to the consequent action. There is a discussion in the literature whether the removal or availability of extrinsic information is necessary for reducing the variability and improving accuracy of movement. For instance, Mulder and Hulstijn (1985) examined the effect of a variety of feedback conditions (proprioceptive, visual, EMG, tactile, and force feedback) in abduction of the big toe. The author reported the superiority of extrinsic feedback (e.g., EMG feedback and force feedback) in comparison to intrinsic feedback (e.g., visual, proprioceptive, and tactile) in achieving proper motor performance. The authors suggest that extrinsic feedback provides an increase in accuracy and facilitates adaptive properties of motor control.
Experimenters use force control tasks to examine principles underlying the neuromuscular systems ability to accomplish task goals. Isometric force production is ideal in determining strategies of the neuromuscular system in goal-oriented tasks because it minimizes problems that may occur when changing position of the limb. For example, a researcher examining a skill like shooting a basketball must consider a myriad of factors that influence the control and accuracy of the shot. The experimenter must consider that during the movement, there are shifts in the internal and external forces acting on the joints involved. The researcher must also consider the stretch reflexes stimulated by changes in muscle length that must cooperate with central commands intended to control the action. A primary concern in controlling both force and position is the filtering action of the musculo-skeletal system, which transforms and delays the effects of central commands. Such delays increase the time required for feedback to affect the trajectory and adapt the necessary inputs needed to govern accurate control of rapid responses. Because the control of limb position requires the central nervous system to scale the forces developed by muscles in order to overcome opposing loads, analyzing the strategies available to control isometric force seems like a necessary step toward understanding the general principles underlying movement.

The motor commands regulating force may be influenced by several properties of the muscle. Researchers have shown that the contraction type (e.g., Christou & Carlton, 2002), development (e.g., Pease & Rupnow, 1983; Poston et al., 2008a), and effector (e.g., Christou, Zelent, & Carlton, 2003) influence the variability in discrete force control tasks. It should be noted that most studies on discrete force control have examined force control of the limbs. There have been few studies comparing force control in the orofacial articulators and limbs. Orofacial articulators have been shown to contain sensory afferents that connect with more central sources
(e.g., brainstem), whereas the limbs have sensory afferents that connect with more peripheral sources (e.g., spinal cord) (Gentil & Tournier, 1998). Comparisons between the limbs and oral effectors would give insights on how individuals regulate factors used to produce impulses. Additionally, auditory feedback seems more advantageous for oral factors due to the use of auditory feedback in speech and music (Sussman, MacNeilage, & Lumbley, 1974); whereas, visual feedback seems more advantageous for the limbs in reaching and aiming (Zelaznik, Hawkins, & Kisselburgh, 1983).

The motor system adapts throughout the lifespan. As individuals age, there are a myriad of factors suggested to produce decrements in motor actions. Typically, older adults are characterized with slower and more variable actions (Light, 1990). Accuracy decrement in motor actions have been suggested to result from a reduction in fast-fatigable type 2 motor units, slower reflex responses, decreased discharge rate, decrements in visuomotor processing, and reduced cognition (see Enoka et al., 2003). More specifically, in discrete force control tasks older adults have been suggested to be more variable in regulating the rate of force production (Christou & Carlton, 2001). The authors reported age-related differences in discrete force control (i.e., older adults were found to be more variable); whereas, there were no group differences in force variability in continuous force control. In discrete force control, individuals must regulate the rate of force production; whereas, in continuous force control individuals regulate the maintenance of force. In discrete force control, individuals must also process information about their performance post-trial. This method of presenting feedback (i.e., offline) may cause older adults to be more variable in producing force in the subsequent attempt.

In discrete force control studies, visual feedback about performance is usually presented along with the criterion template. Older adults may have difficulty processing the visual
Feedback information post-trial. Cortical structures in the right hemisphere have been
demonstrated to mediate visual-spatial tasks. The right-hemisphere hypothesis of aging suggests
that older adults are more variable in tasks that are right-hemisphere mediated (i.e., visual-
spatial) in comparison to the left hemisphere (audio-verbal tasks) (see Dolcos, Rice, & Cabeza;
2002). Christou and Carlton (2001) suggest that older adults have difficulty regulating a
temporal component in discrete force control tasks. However, it is unclear if the extrinsic
feedback given post-trial or the time to peak force requirements is driving the force variability
differences between older and younger adults. Presenting individuals with different modes of
sensory feedback may help resolve this issue as older adults seem to be less variable in tasks that
are mediated with auditory and verbal motor (Golderstein & Shelly, 1981).

The purpose of this investigation was three fold: 1) to determine whether a particular
modality of sensory feedback facilitates accuracy and reduces variability in discrete force control
tasks 2), to determine whether a particular effector is more accurate and less variable with a
particular mode of feedback, and 3) whether the nature of the task or sensory feedback influences
age-related differences in force control.
CHAPTER 2
LITERATURE REVIEW

2.1 MODELS OF FORCE VARIABILITY

The ability of individuals to discriminate between levels of force has been a topic of inquiry for over a century (Fullerton & Cattell, 1892). The variability in which individuals discriminate between magnitudes has served as a window into the nature of mental processes governing movement. In Fullerton and Cattell’s (1892) seminal paper, the investigators sought to determine a relation between the intensity of a stimulus and the just noticeable differences between magnitudes in a series of experiments. Using a custom-made dynamometer, the experimenters asked participants to pull on the handle of the dynamometer a given magnitude (e.g., 2 kg). The participants were informed of their error of the actual pull. The investigators reported a square-root relation between the force magnitude and variability. The authors proposed that individuals’ ability to discriminate between stimuli are based on the sensation perceived by the individual.

Since Fullerton and Cattell’s initial investigation the relation between force level and force variability has been studied extensively and several models of the force-force variability relation have been proposed. The models serve as explanations to account for the speed-accuracy trade-off that is commonly seen in most behavioral tasks (Fitts, 1954). Fitts’ seminal paper demonstrates there is a logarithmic relation between task difficulty and movement time. The logarithmic relation suggests there is a fixed information processing capability in the human motor system. Schmidt et al. (1979) provided the first theoretical account for errors seen in aiming tasks, and reported a linear relation between impulse and impulse error. The authors suggest that errors in the resulting movement were not related to central programming sources of
error but to the variations in the neuromuscular system involved with the movement. There have been several critiques of Schmidt et al. findings of a linear relation between force level and force variability; Newell & Carlton (1988) and Sherwood et al. (1988) suggest different forms of the force-force variability function. Studies that employ a wide range of force levels and control the temporal duration of force pulses have found that variability in force production increases as the level of force increases but in a negatively accelerating manner. This has led to a model of discrete force variability where variability is a function of the time to peak force and the required force level (e.g., Carlton et al., 1993).

There is discussion about whether extrinsic task demands set by the experimenter or intrinsic characteristics of the sensorimotor system are governing impulse variability. Individuals tend to optimize actions in order to accomplish goals, typically with smooth force-time trajectories. A smooth movement or profile is usually characterized by a minimization of “jerk” or acceleration derivative (Hogan & Sternad, 2007). This strategy of force production would be optimal in discrete force control task in matching a specific impulse shape. If sensory feedback plays a role in adapting a smooth profiles strategy, different sensory modalities (i.e., vision and audition) may differentially impact force control. These findings would give insights about how individuals adapt smooth movement profiles.

Harris & Wolpert (1998) suggest that individuals select an optimal trajectory to minimize the final end-point variance in the presence of signal-dependent noise. The authors support this premise with a series of tasks carried out by eye movements, one-joint, and two-joint arm movements. The authors report stereotypical Gaussian profiles in the presence of white control noise and infer that individuals must select these profiles in order to accomplish tasks in the presence of neural noise. The hypothesis proposed by Harris and Wolpert (1998) would suggest
that the greater the magnitude of the stimulus, the greater the noise that might accompany the command. The findings of Harris and Wolpert are similar to Schmidt et al. (1979) that suggest that errors in the resulting movement arise due to properties of the neuromuscular system.

The type of muscular contraction in discrete force control tasks can influence the observed task variability and have significant effects on the force-force variability relation. For example, Christou et al. (2003) have shown that the contraction type performed can elicit differences in force variability in discrete force tasks. Christou et al. had participants perform isometric, eccentric, and concentric contractions in the quadriceps with a criterion time to peak force of 200 ms. The authors found that eccentric contraction conditions resulted in greater peak force variability in comparison to isometric and concentric contractions. Eccentric and concentric contractions may elicit different strategies to select the required force needed for goal oriented tasks. These results suggested that the produced force and force variability might be a result of different properties of selective recruitment of motor units.

2.2 ELBOW AND JAW BIOMECHANICS

There is a similar relation between muscle structure and muscle function. Muscular structure about the elbow and jaw has both similarities and differences. The mechanical capabilities of a muscle are dependent on the muscle-joint-bone system. The inherent position of the muscle in relation to the joint determines its direction of pull and the length of the moment arm of the muscle fibers. The differences between muscle types and muscular structure of the elbow and jaw muscles allow them to perform a variety of movements and maintain various orientations.

For example, the masseter muscle is divided into deep and superficial sections. The deep masseter originates from the whole length of the zygomatic arch and inserts onto the upper part
of the ramus. The superficial masseter starts from a strong tendon plate at the anterior part of the zygomatic arch and inserts to the lateral surface of the mandibular ramus. The temporalis muscle starts from the lateral side of the cranium and its muscle fibers attach to a tendon that inserts on the coronoid and the inner side of the ramus mandible. The masseter and temporalis muscles are involved in jaw-closing, and are typically characterized by relatively large physiological cross-section areas, large tendinous tissue, large pennation angles, and high priority for force indices (van Eijden, Korfage, Brugman, 1997).

The elbow flexors are comprised of three primary muscles that include the biceps brachii, the brachioradialis, and the brachialis. The biceps is a significant contributor to elbow flexion when the forearm is supinated. This position allows the biceps to generate its highest torque value when the elbow is flexed between 80° to 100°. The brachialis muscle originates anteriorly from the lower one-half surface of the humerus and the medial and later intermuscular septum. The brachialis, which exhibits the largest cross-sectional area of all the elbow flexors, and biceps attach close to the axis of rotation. The brachialis is not affected by the shoulder position or forearm position. The brachioradialis muscle takes a proximal origin lateral of the humerus, runs over the radioulnar joint, and inserts to the base of the styloid process. A unique characteristic of the brachioradialis is due to its location of insertion. The insertion location of the brachioradialis is a long distance from the joint axis and creates the greatest mechanical advantage of all the elbow flexors.

As described above, the jaw and elbow have different muscular architecture and muscular degrees of freedom. However, the joint movements between the elbow and tempromandibular joint (TMJ) are similar. During chewing, the jaw has an up and down movement which is a pure hinge motion. The lower jaw does not move freely but is guided by its joints. These structures
may reduce the number of degrees of freedom. Similarly, the elbow has a hinge like motion during extension and flexion. The forces involved during the hinge-like movements (e.g., bite force and elbow flexor force) could give insight of how neuromuscular system deals with similar movements across joints.

There is evidence to suggest that hinge movements have a common mechanism. Tracy et al. (2007) reported that elbow and knee force variability is correlated in a constant isometric force task. The authors found a strong correlation between SD of force between the elbow flexors and knee extensors across age groups; however, this was only when muscle length was constant. In discrete force control tasks there is evidence to suggest that the upper limbs are less variable than the lower limbs (Christou et al., 2003). Christou et al. (2003) suggested that differences between lower limb effectors and upper limb effectors might result from the amount of motor units available and practice. The authors further suggest that more precise movements are made by the elbow flexors, such as drawing and manipulating objects.

The jaw elevators are used extensively for chewing, biting, swallowing, respiration, and speech production. On average, humans chew approximately 1000 times a day. If practice were a factor mitigating force variability differences across effectors, findings from the proposed investigation would extend the findings of Christou et al (2003). Similarities between jaw elevator and elbow flexor force variability may indicate there is a common mechanism driving the force variability. This mechanism may help regulate the similar joint action between the two effectors.

2.3 NEUROMUSCULAR CONTROL OF THE ELBOW FLEXORS AND JAW ELEVATORS

The movement of the elbow and jaw are important for daily activities. The neuromuscular control of chewing involves movement of the jaw and hence regulation of bite
Activities such as throwing, reaching and grasping, lifting, and pulling involve manipulation of the elbow and hence regulation of flexion force. Both systems are capable of fine-tuning the orientation of the required muscle force by selective activation of motor units (e.g., van Eijden & Koolstra, 1998; Gordon & Ghez, 1987).

A complex interaction of connections within the brain (e.g., primary motor areas, cerebellum, basal ganglia nuclei, thalamus, and other cortical structures) and inherent oscillatory processes among these brain structures affect activity to spinal motor neurons. In jaw closing muscles, activity of neurons in the precentral cortex has been reported in studies examining rhythmic chewing movement in monkeys (Kubota & Niki, 1971). For instance, Hoffman and Luschei (1980) examined neurons of the precentral cortex in monkeys trained to produce constant bite force actions and noted that neurons in the precentral cortex were strictly related to EMG activity in jaw muscles during controlled biting forces. It should be noted that other cortical regions such as the supplemental motor area (SMA) and bilateral activation of the sensorimotor cortex may be involved in the regulation of motoneurons involved with controlling bite force. Moreover, aberrations in the precentral cortex interfere with the ability to produce controlled bite forces (Luschei, Garthwaith, & Armstrong, 1971).

The elbow flexors have been found to be regulated by cortical signals from various brain structures (Ghez et al., 1991). Increased cortical activity in SMA and contralateral primary sensorimotor cortex regions as measured by EEG recordings are positively associated with increased levels of muscle activity as measured by EMG recordings (Siemionow, Yue, Ranganathan, Li, & Sahgal, 2000). In this study, participants produced force to match a required force level using 3 distinct rates, slow, intermediate, and fast to a prescribed force target [35% maximum voluntary contraction (MVC)] and produce force to 4 submaximal targets (10%, 35%,
The authors reported increased EEG activity in SMA and contralateral sensorimotor cortex was positively associated (r-values ~0.8) with the increases of force and rate to peak force of the elbow flexors. It is apparent that the elbow flexors and jaw elevators recruit distinct cortical regions in the regulation of force production. It should be noted that most reports on oral structures usually identify bilateral activation of the sensorimotor cortex; whereas, the elbow flexors are usually identified with contralateral activation. This would suggest that more neural degrees of freedom are involved in the regulation of oral movements in comparison to limb movements.

The subcortical components of the elbow and jaw are distinct. For example, reflex loops from the brain stem have been shown to be essential for regulating jaw movements; whereas, the movement of elbow flexion has a greater influence from spinal reflex loops in the cervical section of the spinal cord (Abbink et al., 1999). The trigeminal nerve system branches into three nerves: the ophthalmic, maxillary, and mandibular nerves. The mandibular nerve innervates the muscle involved with mastication and supplies sensation to the jaw. The elbow flexors are innervated primarily by the musculocutaneous and radial nerve and sensation of the elbow flexors may arise from a variety of nerves from the brachial plexus. The elbow flexors appear to have greater amount of peripheral degrees of freedom involved in regulating the muscles involved for force production; whereas, the mastication muscles receive input from a predominate source, the trigeminal nerve. These differing peripheral control components may affect the two primary means to modulate force production: motor unit recruitment and rate coding.
Common Core Hypothesis

Zehr et al. (2007) proposed that different forms of rhythmic movement have a common central neural control. This is termed the common core hypothesis. However research supporting this hypothesis has been shown for mostly limb actions (Zehr, 2005; Zehr et al., 2007). Findings indicated positive correlations between upper and lower limbs with measurement techniques, such as EMG, kinematics, and force production. These findings have suggested that there is a neural coupling at the spinal and cortical levels as seen with a variety of animals. Zehr (2005) argued that a shared circuitry exists such that common central pattern generating (CPG) elements have a common core regardless of the locomotor task. Their hypothesis was tested with arm movements and had participants perform 3 rhythmical arm and leg tasks. The EMG and reflex modulation amplitudes were measured. Uncoupled patterns of background EMG were reported during rhythmical tasks, but there patterns were coupled during static and discrete actions. A model was provided for interaction between a common CPG timing element for rhythm generation, interneuronal reflex networks and afferent feedback. Accordingly, there have been studies suggesting that timing but not force control is preserved across limbs (Christou & Rodriguez, 2008). These results suggest that perhaps the elbow and jaw may have similar control mechanisms.

Maximal Strength of the Elbow Flexors and Jaw Elevators

Voluntary muscle contraction is controlled by the central nervous system (CNS). An individual uses conscious effort to achieve the required force from a signal originating in the brain. The brain sends the motor command through the nervous system to the motor neuron that innervates muscle fibers. Recently, investigators have used maximal strength as indication of full activation of the CNS.
Maximal strength of jaw muscles has been shown to range between 245 and 1247 N with an average of force produced by individuals of 721 N (Gibbs, 1986; Hidaka et al., 1999). The maximal force values of the jaw have been shown to be influenced by dental status and age (Alajbeg et al., 2006; Zarb & Schmidt, 1994). Alajbeg et al. (2006) reported up to a 25% reduction in MVC force for jaw-opening muscles in elderly adults and up to 70% for individuals who wear dentures. It should be noted that jaw opening muscles have been reported to be 20% weaker than jaw closing muscles (Svensson, Burgaard, & Scholosser, 2001).

Elbow flexors muscles have been found to have a maximum force ranging from 103 to 533 N, with an average force of 216 N in discrete force control tasks (Ofori et al., 2012). The maximal force values of the elbow have been suggested to be influenced by age and time to peak force (Christou & Carlton, 2002).

2.4 AUDITORY AND VISUAL FEEDBACK IN RAPID MOVEMENTS

Feedback is often used to augment performance during training. The efficacy of visual feedback is well known (Bilodeau, 1966; Woodworth, 1899); however, little is known about the impact of auditory feedback during training. Auditory feedback contributes to highly functional movements that involve the oral effectors, such as speaking, singing and cueing movements to sounds in the environment (Adams, Weismer, Kent, 1993). Individuals use non-oral actions routinely to manipulate objects while attending to the loudness and frequency characteristics of sound. A trumpet player may need to monitor precise auditory information to achieve correct oral and finger movements to keep tempo in a large band. Auditory feedback could provide individuals a unique way to minimize errors and can be updated fairly quickly for tasks with longer timescales. Some authors have theorized that deficits in speech production prompt affected individuals to rely more on closed-loop control strategies to compensate for the deficits.
in speech motor control, but it is unclear if this provides functional benefits (McNeil, Weismer, Adams, Mulligan, 1990). As such, investigations on the use auditory feedback for guiding efficient movements of the limbs and oral articulators are warranted.

In the acquisition of novel oromotor actions, auditory acuity has been suggested to play a primary role. Auditory acuity refers to an individual’s ability in choice tasks to discriminate the correct response (Ghosh et al., 2010). A performance measure calculated from choice tasks is a just noticeable difference (JND). The just noticeable difference provides an indication of one’s ability to discriminate from two distinct elements on a stimulus scale. In speech tasks, individuals with greater auditory discrimination create more auditory goal-directed sounds for vowel production due to the many complex sounds in language (Ghosh et al., 2010). Theoretical models on information processing in speech have proposed that learning is guided by auditory and somatosensory targets in the acquisition phase (Guenther, 2006). This also suggests that the quality of the feedback provided, or extrinsic feedback, may aid in the development of a “reference-of-correctness” of the intended auditory sound. Evidence supporting the notion that auditory representations are important during the acquisition phase of a skill can be found in reports suggesting birds reared without exposure to hearing species-specific songs (Johnston, 1988) and acquisition of a second language (Flege, Munro, & Mackay, 1995).

Multiple trials at a task are used to develop a desired reference signal or template for accurate and successful task performance. This reference signal may be used as a means to correct errors during feedback control and anticipate errors in feedforward control. For example, visual feedback during a movement has been shown to influence the accuracy of the movement in many aiming studies (e.g., Khan & Franks, 2000). Visual information about the spatial characteristics of a task has been used to support the relation between movement time and task
difficulty, in order to maintain accurate performance in manipulation tasks (Fitts, 1954). This supports the notion that visual feedback is instrumental for optimal behavior of the manual limb, although there have been studies demonstrating the removal or absence of visual feedback can still lead to goal-directed movements (Humphrey & Wieskrantz, 1969; Jeannerod, 1990).

This absence or removal of visual feedback typically results in decrements in accuracy. Furthermore, the absence of visual feedback prior to movement initiation leads to detrimental performance when the movement is made outside of the participant’s central visual field. For instance, movement time and accuracy decreases when participants must perform tasks across one’s midline or visual “hemi-field” of the contralateral arm (Fisk & Goodale, 1985). This suggests that type of visual information available plays a role in upper limb actions. In a discrete force control tasks, individuals must determine the errors between the actual movement and target movement offline because the action is short by nature and any modifications to the motor command must be made after the movement is completed. However, it is unclear if varying the type of sensory feedback post trial in rapid movement can influence task performance. In a tracking task, Coull et al. (2001) reported visual feedback conditions resulted in less tracking error than auditory feedback conditions during the acquisition phase. The authors suggest the error correction with visual feedback is superior to auditory feedback, thus leading to better task performance during the acquisition phase of learning.

2.5 AGING AND FORCE CONTROL

Older adults have a reduced ability to control rapid discrete actions in comparison with younger adults (e.g., Christou & Carlton, 2001; Haaland, Harrington, & Grice, 1993; Pratt, Chasteen, & Abrams, 1994). Moreover, it appears that older adults have a decreased ability to control low levels of force control (Laidlaw, Bilodeau, & Enoka, 2000). Reduced force control
ability may be explained by models of cognitive aging which suggests that general slowing of
the CNS occurs in older adults (Salthouse, 1996; Welford, 1981). Accordingly, accumulating
evidence suggests that older adults are less efficient at processing more complex visual feedback
than their younger counterparts (Ofori, Samson, & Sosnoff, 2010; Proteau, Charest, & Chaput,
1994; Sosnoff & Newell, 2006).

Increased force variability with aging may be associated with decrements in both sensory
and motor systems. This decline in sensorimotor function can be attributed to a constellation of
factors such as: reduced strength, reduced number of muscle fibers (Lang, Steeper, Cawthon,
Baldwin, Taafe, & Harris, 2010), increased variability of firing rate (Enoka et al., 2003), reduced
tactile sensitivity (Wohlert & Smith, 1998) reduced visuomotor processing (Sosnoff & Newell,
2006), and contraction type (Christou & Carlton, 2002). Even the health status of the older
individual may influence movement variability (Emery, Huppert, & Schein, 1995). However,
the extent to which the sensorimotor decline observed is more pronounced with visual or
auditory feedback remains unclear.

Although, age-related differences in force control have been shown for the oral-facial
system, this has been shown mostly with visual feedback (Ballard, Robin, Woodworth, & Zimba,
2001). Comparisons between the limbs and oral articulators in younger adults suggest the oral
articulators have a less fine-tuned visual-motor integration system in comparison to the upper
limbs (Gentil & Tournier, 1998; van Steenberghe, Bonte, Schols, Jacobs, & Schotte, 1991).
Recent investigations have reported no difference in accuracy of force tasks for the lower lip and
finger if online auditory feedback is provided (Loucks et al., 2010). However, little is known
how the articulators map auditory targets for proper motor actions offline in discrete force
control tasks and how the relation between feedback and variability changes with age.
Statement of the Problem

Studies of discrete force control have provided extensive knowledge concerning the control of movement. Various factors have been found to influence the observed variability. The primary factors used to model variability are time to peak force and force level (Carlton & Newell, 1993). The inability to regulate force production (i.e., force variability) is a concern for individuals but allows researchers to infer the processes underlying the regulation of force production.

Discrete force control tasks are unique in that they require individuals to regulate factors that influence the subsequently produced impulse. In discrete force control tasks, participants produce rapid force pulses with short durations over numerous trials. Variation in discrete parameters such as peak force, time to peak force, and impulse are usually measured. While these discrete measures provide useful measures regarding the consistency of force pulses produced; these variables do not provide enough information about the strategies used to generate specific characteristics of the impulse or how the produced force relates to task performance. For instance, a participant may utilize several impulse strategies to accomplish a peak force.

Visual feedback from the resulting impulse can allow individuals to make comparison between the criterion and their force output. This form of feedback may serve to reduce spatial deviations from the criterion but may not provide enough time-sensitive information in discrete force control tasks to effectively reduce temporal variability. The influence of other forms of exteroceptive feedback has not been examined on discrete force production. Evidence has suggested that auditory feedback provides more time-sensitive information than visual feedback (e.g., Helfer, 1997). Auditory feedback also is more commonly used for oral effectors and
speech tasks than manual effectors. While it is clear that feedback facilitates force production accuracy, it is unclear how feedback influences movement variability. Thus, determining the underlying sensory processes driving force variability in discrete force control tasks is essential.

Data regarding to age-related differences in discrete force variability are essential as they can provide insight on how the CNS organizes movements over the course of an individual’s lifespan. Older adults are usually characterized with slower movements and have decrements in visual motor processing (Pratt et al., 1994). However, there are conflicting findings on whether these age-related differences in force variability are consistent across effectors (Ballard et al., 2001). It should be noted that auditory feedback is used more frequently by the oral-motor system and perhaps age-related differences in force variability across effectors may depend on the mode of sensory feedback.

The main purpose of this dissertation, over two experiments, was to determine how feedback influences accuracy and variability in discrete force tasks and whether the mode of feedback and effector interact in determining force variability. Additionally, how age influences variability was examined.

It is unclear how variability is influenced by feedback or the mode of feedback presentation. The mode of feedback presentation may influence variability and accuracy in the time to peak force and/or shape of the produced force pulse. The shape of the force pulse specifies the position and time characteristics of a resulting movement. It is expected that feedback with the greatest spatial-temporal detail will lead to the most accurate performance and rapid acquisition. Second, it is unclear if age-related differences in force variability and accuracy exist across elbow flexors and jaw elevators as a function of sensory feedback in discrete force control tasks. It is expected that effector differences in force variability exist for the upper limb
and jaw. It is anticipated that the two different effectors will be influenced by the mode of sensory feedback provided. Specifically, it is expected that jaw elevators will be less variable with auditory feedback and more variable with visual feedback in comparison to the elbow flexors. Over trials, auditory feedback conditions should result in a decrease in force variability and an increase in force accuracy in comparison to visual feedback conditions. If auditory feedback conditions result in similar force variability across effectors in discrete force control tasks for younger adults, then age-related differences in force variability under auditory or visual feedback conditions may suggest there are specific sensory processes that declines with aging for discrete force control tasks. It is expected that older adults’ force pulses will be more variable in the elbow flexors than the jaw elevators in comparison to younger adults and that this difference will depend on the mode of sensory feedback.
CHAPTER 3

EXPERIMENT 1

3.1: DOES SENSORY FEEDBACK INFLUENCE FORCE PRODUCTION ACCURACY AND SHAPE?

Sensory feedback is essential for adaptive motor control. Motor behavior and how individuals perceive and control actions has received inquiry and scrutiny for over a century (e.g., Fullerton & Cattell, 1892; Woodworth, 1899). When an individual generates an action from rest in a brief period of time, one has little time to attend to the online sensory feedback during the movement (e.g., Christou et al., 2007; Keele, 1968; Woodworth, 1899). As such, repeated attempts of a rapid action are prone to error due to the complex organization of the neuromuscular system. In order to reduce errors, the neuromuscular system must adapt control processes in order to facilitate precise motor control. In goal directed actions, researchers have proposed several factors that may influence the variability from the initial motor command (e.g., Carlton et al., 1993; Loucks et al., 2010; Newell & Carlton, 1988). In rapid force control tasks, the desired target force and time to peak force are critical factors to be considered for accurate performance (Carlton et al., 1993). Most of these reports have provided the participant with offline or online visual feedback to estimate the limits of accuracy and consistency of the neuromuscular system. However, little attention has been given to other sensory modalities and their role on force control. For instance, when playing an instrument one must attend to auditory information for precise actions. Thus, the purpose of this investigation is to examine whether offline visual and auditory feedback can differentially influence force control in the elbow flexors.
Strategies used by an individual to reduce error on subsequent attempts of a desired endpoint goal have received much attention (e.g., Carlton et al., 1993; Gordon & Ghez, 1987; Poston et al., 2008b). Visual feedback from a completed movement can improve task performance on forthcoming trials (e.g., Bernier, Chua, Franks, & Khan, 2006). Offline processing of feedback can be especially useful for actions that are brief in duration or in settings where visual feedback is provided too late in the movement to allow for online corrections (Hinder, Tresilian, Riek, & Carson, 2008). In discrete force control tasks, individuals attempt to replicate force-time criterion goals over numerous trials. Visual feedback of performance is typically presented after each attempt. Investigators have shown that individuals can adapt control processes used to regulate goal-directed force pulses over several trials. As such, these control processes may use this visual information to adapt the neuromuscular system to meet task demands. Results from discrete force control tasks have inferred that force variability results from a predominant central control strategy (e.g., Carlton et al., 1993). Central control processes used to generate rapid force pulses are characterized by the required impulse rate desired for accurate movement (Vaillancourt et al., 2007).

Although offline visual feedback has been shown to impact control processes used in rapid goal-directed actions, auditory feedback can also be useful in rapid tasks (e.g., Woodworth, 1899). Auditory feedback is useful to cue movement onset and sound localization. For instance, Heap and Wyke (1977) have shown that auditory feedback can influence movement direction in rapid arm movements. Moreover, reaction times to auditory signals have been shown to be faster than responses to visual signals in arm movements (e.g., Sugano, Nakajima, Yokokawa, 1985). This suggests that auditory information may provide more temporal information in comparison to visual feedback. Additionally, there is accumulating evidence to suggest auditory
feedback can provide individuals with a spatial representation of the environment (e.g., Aytekin et al., 2008). This spatial representation is usually inferred from binaural information, such as interaural level and time differences, and monaural spectral features contained in the auditory feedback at each ear. Online auditory feedback has been shown to elicit distinct audiomotor control processes in force pulse regulation (e.g., Ofori, Loucks, Sosnoff, 2012). However, little is known how offline auditory feedback influences force variability.

Investigators have used various analysis procedures to assess variability in rapid tasks. In discrete force control tasks, researchers have used measures such as the CV of specific impulse characteristics. The CV is computed by taking the SD of peak force over several trials and dividing that value by the mean over those trials. The CV provides a normalized assessment of variability because SD of peak force is known to concomitantly increase with increases of mean force level. This measure provides a global assessment of the individual’s force variability for a specific condition. Typically, CV decreases in a nonlinear fashion with increases of force level (e.g., Ofori, Sosnoff, & Carlton, 2012).

The purpose of Experiment 1 was to examine whether various forms of sensory feedback influence force control of the elbow flexors. Specifically, the current experiment examined the influence of sensory feedback on accuracy and variability in discrete force control tasks, and whether accuracy and variability changed with practice. By providing individuals with offline auditory, grayscale, and time-series visual feedback, the impact of sensory mediated control processes force variability may be inferred. It was hypothesized that SD and CV of time to peak force would be lower in auditory feedback conditions in comparison to no feedback, time-series, and grayscale visual feedback conditions. Additionally, decreases in CV over trials were expected for all conditions, with the no feedback conditions exhibiting the smallest changes from
the first block to the last block of 30 trials. Differences in the level of force variability across sensory feedback conditions were not expected.

3.2 METHOD

3.2.1. Participants

Seventy-two (72) volunteers (33 female) with no history of hand, shoulder, wrist, and elbow pathology or current upper extremity injuries were recruited from the community and student population of the University of Illinois in Urbana-Champaign. All participants were right hand dominant. An institutional review board consent document was given to the each participant. Each participant was randomly assigned to one of four feedback groups (See Experimental Procedures).

Apparatus

A D-ring handle was attached to a strain-gauge force transducer (Gould-Statham UC2, interfaced to UL4-200 load cell). The D-ring and load cell assembly was secured to a table top. The participant sat at the table and grasped the handle with the right hand. When grasping the handle, the participant’s right arm was abducted to shoulder height, with 45° of horizontal flexion at the shoulder. The elbow was flexed 90°. The handle and force transducer assembly was mounted perpendicular to the lower arm and allowed measurement of force produced during flexion about the elbow (See Figure 3.1).

In order to provide feedback to the participant, a computer monitor was placed on the table. The monitor was 65 cm from the participant. The monitor’s diagonal viewing area was 55.9 cm. The screen resolution was 1680 by 1050 pixels. Custom programs written with LabView 2011 (Austin, TX) were used to collect force data from the strain gauge at 1000 Hz. In order to provide auditory feedback to the participant, headphones (Sennheiser USA, Older Lyme,
Connecticut) were placed on the participant’s ears. The headphones were circumaural headphones with 32 dB attenuation of external noise. The audio gain level was set at a comfortable level of hearing.

**Figure 3.1 D-ring hand interfaced with the force transducer (TOP). Transverse view of the participant interfaced with the D-ring handle (BOTTOM).**
3.2.2. Discrimination Test Procedures

In order to compare force production accuracy and shape across feedback modalities, preliminary discrimination tests were administered to set equitable feedback gain ratios.

**Grayscale Discriminability Test.** A two-interval two-alternative force-choice test was used to assess visual discriminability for judging whether the second of two grayscale images were “brighter” or “darker” than the first. The grayscale images were presented based on a Red, Green, and Blue color scale in which each color ranged in brightness from 0 to 255. Grayscale is created when each color’s brightness level is equal to the other. For example, Black represents 0=Red, 0=Green, & 0=Blue, and White represents 255=Red, 255=Green, & 255=Blue. Each participant was first presented with a grayscale image that represented 50% of the grayscale range (127=Red, 127=Green, & 127=Blue). The second image presented was 12% (127 ± 15 =R=G=B) “brighter” or “darker” than the first. Participants completed 6 trials and if the participant was correct on 66% or more of the trials they would complete 6 more trials at 6% (127 ± 8 =R=G=B), this procedure would continue until the participant scored lower than 66%. The last test condition receiving a score 66% or greater served as the participant’s visual discriminability.

**Visual Acuity Test.** A forced choice test was used to determine the spatial resolution limit or threshold (Bach, 1996). In this procedure, an optotype, the Landolt C was used. An optotype is a standardized symbol for testing vision. The procedure started with an easy to recognize optotype, and having the participant indicate the orientation of the gap in the Landolt C. The Landolt C was presented on the monitor in one of eight positions. The participant presses one of eight buttons which are spatial arranged on the numeric keypad according to the Landolt C’s gap. The eight positions were left, right, up, down, and diagonal direction between left, right, up and
down. Depending on the correctness of the response, an easier or more difficult to recognize optotype was presented, ultimately aiming to determine the spatial resolution limit or threshold. The computer program selected the size of the Landolt Cs on a logarithmic scale using the "Best PEST" algorithm (Best Parameter Estimation by Sequential Testing), a modern procedure to measure psychophysical thresholds.

**Adaptive Pitch Test.** Similar to the Visual Adaptive Brightness Test, a two-interval, two-alternative forced-choice paradigm was used to measure difference threshold for judging whether the second of two pure tones was “lower” or “higher” in pitch. A 500 Hz tone was presented followed by a second tone either 96 Hz below or above 500 Hz. If the participant made 3 correct guesses in a row, he or she attempted to discriminate tones that were +/- 48 Hz from the base 500 Hz tone. This procedure continues until the participant made 3 incorrect guesses in a row or until 8 trials were completed at a discrimination level without 3 correct or incorrect responses in a row. The participant’s discriminability was determined by the average frequency difference between the two tones for the incorrect guesses. This adaptive pitch test can reliably measure frequency discrimination only when discrimination ability is greater than 60 Hz. For comparison, at the 400 to 600 Hz frequency range, two adjacent notes on a piano keyboard are approximately 30 Hz apart. If a participant’s frequency discriminability was poorer than 60 Hz, the participant was excluded from the study.

**Cross-Modality Matching.** The discrimination tests served to establish a gain ratio between feedback and force so that the feedback changed with force level similarly across feedback modalities. The strategy was for both visual and auditory feedback to have one unit of force be represented by one discriminable difference in sensory information. A grayscale value of zero (black) was set to 0.0 N of force and a grayscale value of 127 was set to 90 N. It follows
that each increment of grayscale value represented 0.7 N. The Grayscale Discrimination Test results revealed that the change that could just be discriminated was 3 levels of grayscale. Individuals could discriminate between RGB levels 124 and 127, but not between 125 and 127. Therefore, the grayscale discrimination level equaled 2 N. The 2 N value was used to represent 1 discrimination level for both the visual and auditory feedback conditions.

The Visual Acuity Test indicated that 0.29 mR could be visually discriminated. Based on the monitor vertical resolution and the monitor to participant distance used in this study, 0.64 pixels could be discriminated. Based on the discrimination to force level ratio used for grayscale, each 0.64 pixels was set to represent 2 N. On the monitor, the criterion peak force (90 N) was set to 60 vertical pixels. The Adaptive Pitch Test revealed that a change of frequency of 10 HZ could be discriminated. A frequency value of 500 Hz was set to 0.0 N. A value of 90 N was set to 950 Hz. In this way, the ratio between sensory discrimination and force level was the same for all visual and auditory feedback conditions.

3.2.3. Experimental Procedures

Estimation of Maximum Voluntary Contraction (MVC). To determine a participant’s MVC, the participant was asked to produce a rapid maximal elbow flexion force with a time to peak force near 200 ms. Participants received feedback about the time to peak force after each trial. Ten MVC trials were recorded. If there were fewer than three trials with a time to peak force between 180-220 ms, additional trials were performed until 3 trials were obtained. The MVC was specified as the highest peak force value from trials with a time to peak force between 180 and 220 ms.
3.2.4 Feedback Conditions

Each participant performed 90 trials with a criterion peak force of 90 N with a criterion time to peak force of 200 ms at each feedback condition. Ninety Newtons was chosen based on a previous experiment that showed that force variability at 90 N is correlated with variability at a wide range of force levels (Ofori et al., 2012). There was 5 s rest given between.

Visual Feedback Condition A force-time template in the form of a Gaussian curve with criterion peak force presented at 60 pixel height and zero force at 0 pixel height was used to represent the force time requirements for the task. Participants were instructed to match their force output in the form of a time series plot to the Gaussian time series template. After each trial, the participant was given visual feedback of their force output in comparison to the Gaussian template. One second of the participant’s experimental trial was provided as visual feedback with the Gaussian template plotted along the first 400 ms. This condition provided individuals with a visuo-spatial template to discern errors between desired peak force, time to peak force, and impulse shape and produced peak force, time to peak force, and impulse shape.

Grayscale Feedback Condition. The criterion response and visual feedback were provided by a change in grayscale based on force level as a function of time. The criterion appeared as a 400 ms duration light flash. At time zero and at time 400 ms the grayscale was set to black (i.e., 0 on the RGB scale). At the peak of the criterion force-time curve (i.e., 200 ms) the red-green-blue brightness levels were set at 127. This transient form of feedback was used in order to replicate the manner individuals received auditory feedback (see next section). Participants were instructed to produce a force output to match the light-based criterion. Each change in brightness (grayscale) occurred every 1 ms until the end of the template or force pulse.
The template was Gaussian in form. After each trial, the participant was given the visual template followed by the visual feedback based on their force output.

**Auditory Feedback Condition.** The criterion response and visual feedback were provided by an audio signal to a set of headphones. The criterion peak force level was represented by a pure tone of 950 Hz. As in the other feedback conditions, the criterion template was Gaussian in form. Zero force was represented by a 500 Hz tone and as force level increased the frequency of the tone increased.

**No Feedback Condition.** Participants were verbally provided their maximum force and time to peak force for each MVC trial. Participants were then shown the criterion Gaussian waveform before the start of the testing session. For each trial, the participant was instructed to produce the criterion template force pulse; however, post-trial feedback of each attempt was not provided.

3.2.5. **Data Analysis**

Data were acquired and analyzed using LabView 2011 software (National Instruments, Austin, TX) & NLReg 6.5. Peak force, time to peak force, impulse, and peak rate of force up to peak force were obtained from each trial. Ninety trials were used for data analysis. Means, standard deviations (SD), and coefficients of variation (CV) of the first 30, second 30, and last 30 experimental trials were calculated.

Force production accuracy was assessed in two additional ways. First, absolute error was calculated on peak force and time to peak force. Absolute error was calculated by taking the absolute value of the actual peak force or time to peak force minus the criterion peak force or time to peak force, respectively. Second, root mean square error between the criterion
waveform and participant’s force pulse was calculated for each trial with the criterion and trial force-time curves aligned at force initiation.

Characteristics of the force shape were assessed in three ways. First, the force pulse was analyzed by integrating force as a function of time and fitting the data to a 3 parameter logistic function (i.e., sigmoidal). The goodness of fit was determined with adjusted r-square values. The goodness of fit between the criterion Gaussian template and the 3 parameter logistic function is 0.998. The logistic function used to fit the integrated force template is provided in equation 1. In the logistic function, $a$ is the asymptote of the function (i.e., impulse), $b$ is the duration of the impulse, and $x_0$ is the time the inflection point. These values provided indication of force pulse accuracy. Means, SD, and CV of the inflection point, which provides an indication of the symmetry of force pulse, were used for analysis.

$$y = \frac{a}{1 + \exp\left(-\frac{x-x_0}{b}\right)}$$

(1)

Second, the skewness of the force pulse was assessed. Skewness is the asymmetry of a probability density function (e.g., Gaussian curve). A negative value indicates the function is left-tailed and a positive value indicates the function is right-tailed. A symmetric distribution such as a normal distribution has a skewness of 0. Third, kurtosis of the force pulse was assessed indicating the relative peakedness of the force pulse. Kurtosis is another measure that provides insight of the shape of the distribution. The kurtosis for a standard normal distribution is 3. Values greater than 3 indicate a more “peaked” distribution; whereas, values less than 3 indicate a more “flat” distribution (e.g., a uniform distribution would be the extreme case). Skewness and kurtosis were calculated using Pearson coefficients.
A 3-way mixed model repeated measures ANOVA with 2 between group factors, gender (2 levels: male and female) and feedback (4 levels: visual, grayscale, auditory, and no feedback) and 3 levels of the within group factor [trial blocks (1-30, 31-60, 61-90)] was conducted. Gender effects were reported when significant, otherwise data was summed over gender. Additionally, post hoc analysis performed with a Bonferroni correction was used to examine significant interactions.

Figure 3.2 The criterion template and the mean produced force trajectory for each feedback condition.
3.3. RESULTS

3.3.1 Maximal voluntary contraction

There were no significant differences in MVC levels across feedback conditions \([F < 1]\). The average maximum force value was 154 N. There were significant difference in MVC across gender \([F(1,64) = 64.8, p<0.05]\). Males (182 N) produced greater maximum force than females (124 N).

3.3.2 Force Accuracy

Mean peak force provides an indication of whether participants produced the criterion level of force (see Figure 3.2). Mean peak force was not influenced by feedback condition but mean peak force significantly decreased over trials \([F(2,136) = 3.35, p<0.05]\). Post hoc analysis revealed a greater mean peak force in the first block than the second and third blocks (see Figure 3.3). Analysis on AE of peak force revealed a significant effect of feedback \([F(3,68) = 8.34, p<0.05]\) and trial \([F(2,136) = 4.28, p<0.05]\) (see Figure 3.4). Post hoc analysis revealed that AE was greater in the no feedback condition (22.80 N) than the grayscale (15.29 N), auditory (10.65 N) and visual (12.56 N) conditions. The trial effect resulted from greater AE in the first block of trials (17.16 N) than the second (14.26 N) and third (14.56 N) blocks. Standard deviation of peak force decreased with increases in trial blocks \([F (2,136) = 23.07, p<0.05]\) (see Figure 3.5). Post hoc analysis revealed greater SD of peak force in the first block (14.8 N) than the second (10.7 N) and third blocks (11.2 N). Statistical analysis also revealed a feedback \([F(3, 68) = 4.69, p<0.05]\) and trial effect \([F(2,136) = 21.85,p<0.05]\) on CV of peak force (see Figure 3.6). Post hoc analysis revealed that CV was greater in the no feedback conditions (0.18) than auditory (0.13) and visual feedback (0.13) conditions. There was greater CV in the first block (0.17) than the second (0.13) and third block (0.14) of 30 trials.
Figure 3.3 Mean peak force across 3 trial blocks.

![Graph showing mean peak force across 3 trial blocks]

Figure 3.4 Mean absolute error of peak force from each feedback condition across 3 trial blocks.

![Graph showing mean absolute error of peak force across 3 trial blocks]
Figure 3.5 Standard deviation of peak force as a function of 3 trial blocks (1-30, 31-60, & 61-90).
Figure 3.6 Coefficient of variation of peak force from each feedback condition across 3 trial blocks.

Mean, SD, and mean AE of time to peak force did not show any significant changes across feedback or trial blocks. The average mean time to peak force was 216 ms with a SD of 58 ms. The average AE was 54 ms. Feedback was found to influence the CV of time to peak force \([F(3,68) = 3.08, p<0.05]\) (see Figure 3.7). Post hoc analysis revealed the auditory and visual feedback conditions were significantly different from each other.
Figure 3.7 Coefficient of variation of time to peak force from each feedback condition across trial blocks.

Mean squared error (MSE) provided an indication of force production accuracy. Mean squared error was influenced by feedback \[F(3,68) = 3.02, p<0.05\] and decreased as trial blocks \[F(2,136) = 6.112, p<0.05\] increased (see Figure 3.8). Post hoc analysis revealed greater MSE in the no feedback conditions (1103.90 N^2) than the grayscale (690.16 N^2), auditory (643.59 N^2), and visual feedback conditions (647.70 N^2). The trial effect resulted from greater MSE in the first block (937.83 N^2) than the second (693.83 N^2) & third block (682.35 N^2).
Mean impulse provides an indication of the aggregate force over time. The mean, SD, and CV of impulse were not significantly influenced by feedback but the mean \(F(2,136) = 3.62, \ p<0.05\), SD \(F(2,136) = 13.47, \ p<0.05\), and CV \(F(2,136) = 25.14, \ p<0.05\) of impulse decreased with trial block. Post hoc analysis revealed that the mean, SD, and CV of impulse was significantly greater in the first trial block as compared to the second and third blocks (see Figure 3.9, 3.10, 3.11).
Figure 3.9 Mean impulse across 3 trial blocks.

Figure 3.10 Standard deviation of impulse across 3 trial blocks.
3.3.3 Force Production Shape

Mean skewness provided an indication of whether participant’s produced a symmetric force pulse. Across trial blocks skewness values decreased and the form of the decrease depended on the feedback condition. Figure 3.12 illustrates the decrease in skewness across trial blocks of one participant. Statistical analysis revealed a trial effect \( F(2,136) = 4.52, p<0.05 \), feedback effect \( F(3,68) = 2.65, p<0.05 \), and feedback x trial interaction \( F(6,136) = 3.18, p<0.05 \) (see Figure 3.13). The feedback x trial interaction was the result of a decrease of skewness in the auditory condition from the first block (0.07) to the second block (0.02) and third block (0.03); whereas, there was an increase of skewness in the no feedback, grayscale, and visual feedback conditions from the first block (-0.20; -0.09; -0.10) to second block (-0.15; -0.03; 0.01) and third block (-0.12; -0.03; 0.02). Generally, skewness decreased over trials.
Figure 3.12 Example trials from an individual during the first and third blocks.
Mean kurtosis provided an indication of the peakedness of the force pulse. A feedback effect resulted from greater kurtosis in the no feedback condition (1.71) in comparison to the auditory feedback condition (1.54) \( F(3,68) = 3.05, \ p<0.05 \) (see Figure 3.14). In all cases, kurtosis was significantly smaller than 3, indicating a less peaked distribution than a normal distribution.
The integrated force pulse was fitted with a logistic function. The correlation between the impulse function and the logistic function resulted in an adjusted $r$-square from each unique trial ranging from 0.86-0.99. The correlation was not influenced by either feedback or trial blocks.

The mean inflection point for each feedback condition provided a descriptor of the symmetric point of the logistic. There was a significant effect of feedback on mean inflection point [$F(3,68) = 2.7$, $p=0.05$]. Greater inflection point times were found in the auditory (194 ms) and no feedback (193 ms) than the visual (170 ms) and grayscale (172 ms) feedback conditions. Trial blocks influenced the SD of the inflection point [$F(2,136) = 24.1$, $p<0.05$]. The first trial block (31ms) had significantly greater SD than the second (23 ms) and third trial blocks (22 ms). Trial [$F(2,136) = 24.1$, $p<0.05$] and feedback [$F(3,68) = 25.9$, $p<0.05$] influenced the CV of the inflection point. Greater CV was found in the first block (0.19) than the second (0.15) and third
blocks (0.14). The feedback effect resulted from greater CV in the visual feedback (0.23) than the no feedback (0.15), grayscale (0.14) and auditory feedback conditions (0.12) (see Figure 3.15).

Figure 3.15 Coefficient of variation of inflection point from each feedback condition across trial blocks.

3.3.4 The relation between feedback discriminability and force accuracy

Table 3.1 indicates the group mean and standard deviations of each feedback group before and after experimental testing.
Table 3.1  Discrimination scores from Sensory Tests of Experiment 1

<table>
<thead>
<tr>
<th>Sensory Test</th>
<th>Mean</th>
<th>SD</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Pre-Test</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Auditory (Hz)</td>
<td>20.30</td>
<td>21.50</td>
</tr>
<tr>
<td>Visual (mR)</td>
<td>0.36</td>
<td>0.09</td>
</tr>
<tr>
<td>Grayscale (levels)</td>
<td>5</td>
<td>2</td>
</tr>
<tr>
<td><strong>Post-Test</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Auditory (Hz)</td>
<td>10.2</td>
<td>9.00</td>
</tr>
<tr>
<td>Visual (mR)</td>
<td>0.28</td>
<td>0.07</td>
</tr>
<tr>
<td>Grayscale (levels)</td>
<td>5</td>
<td>3</td>
</tr>
</tbody>
</table>

To determine if one’s discriminability is related to one’s accuracy and variability, Pearson correlations were computed between discriminability scores and accuracy and variability measures (see Table 3.2). Generally, auditory feedback discrimination was correlated with measures of accuracy in the first block of trials; whereas, visual and grayscale discrimination showed significant correlations with performance accuracy in the second or third trial blocks.
Table 3.2 Correlations between force production accuracy and discriminability scores

<table>
<thead>
<tr>
<th>Dependent Variable</th>
<th>Feedback Condition</th>
<th>Block 1</th>
<th>Block 2</th>
<th>Block 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>SD of Peak Force</td>
<td>Grayscale</td>
<td>-0.21</td>
<td>0.04</td>
<td>0.12</td>
</tr>
<tr>
<td></td>
<td>Auditory</td>
<td>0.61*</td>
<td>0.21</td>
<td>0.01</td>
</tr>
<tr>
<td></td>
<td>Visual</td>
<td>-0.01</td>
<td>0.48*</td>
<td>0.17</td>
</tr>
<tr>
<td>SD of Time to Peak Force</td>
<td>Grayscale</td>
<td>-0.04</td>
<td>0.02</td>
<td>-0.21</td>
</tr>
<tr>
<td></td>
<td>Auditory</td>
<td>0.64*</td>
<td>0.17</td>
<td>0.23</td>
</tr>
<tr>
<td></td>
<td>Visual</td>
<td>-0.11</td>
<td>0.22</td>
<td>-0.23</td>
</tr>
<tr>
<td>Mean Squared Error</td>
<td>Grayscale</td>
<td>0.14</td>
<td>0.42*</td>
<td>0.59*</td>
</tr>
<tr>
<td></td>
<td>Auditory</td>
<td>0.47*</td>
<td>0.25</td>
<td>0.07</td>
</tr>
<tr>
<td></td>
<td>Visual</td>
<td>0.30</td>
<td>0.30</td>
<td>0.26</td>
</tr>
</tbody>
</table>

*p < .05, **p<.01
3.4. DISCUSSION

The purpose of Experiment 1 was to examine how feedback influenced discrete force production accuracy, variability and shape over practice. While it is clear that feedback facilitates response accuracy, it is not clear how feedback influences variability. Post-trial auditory feedback, grayscale feedback, and spatial visual feedback were examined along with a no feedback condition. The ratio between force and sensory discrimination was equated across feedback conditions. It was hypothesized that auditory feedback would provide greater timing information which would result in lower timing variability and greater consistency in force production shape. Practice was also expected to decrease variability as measured by CV for all feedback conditions. It was expected that responding without feedback would result in minimal improvements in accuracy but decreased variability. Differences in the level of force variability were not expected across auditory, visual, and grayscale feedback conditions.

In general, the results from Experiment 1 supported these hypotheses. Feedback led to improved accuracy and lower variability over trials as compared to no feedback. As hypothesized, there were no differences in accuracy and variability among feedback types except that auditory feedback resulted in lower timing variability. This was seen in significantly lower CV of time to peak force and lower CV of inflection point. Thus the only differences between visual, grayscale, and auditory feedback occurred with temporal measures. Practice had a significant effect on all the dependent variables except for time to peak force. For all the dependent variables, the first block had greater variability and less accuracy than the second and third blocks. Sensory discriminability scores were also moderately correlated with both force production accuracy (MSE) and variability scores (SD of peak force, SD of time to peak force). Taken together, the results suggest that sensory feedback influences force production accuracy,
variability, and shape; and adaptations made early in learning may be, in part, related to one’s discriminability.

Several models have been proposed to account for the force-force variability relation. These models have suggested central and peripheral factors that may be driving the observed force variability. For example, an internal model has been suggested to predict the next state based on the motor command and the current state of the motor system (Miall & Wolpert, 1996; Harris & Wolpert, 1998). One prediction of the aforementioned internal model is that the CNS selects a symmetric shape in the presence of signal dependent noise resulting in a reduction in variability. This is referred to as the minimum variance hypothesis. Signal dependent noise is a result of the various neurons influencing the motor command (Harris & Wolpert, 1998).

Feedback is thought to play a negligible role in the planning and execution of rapid force pulses.

Data from the current study contradict the minimum variance hypothesis. The results indicated that feedback played a role in motor planning. The type of feedback may influence the timing of the force pulse which may result in varying symmetric and non-symmetric shapes. The minimum variance hypothesis also suggests that the skewness of force pulses should be zero if the CNS selects symmetric impulses in the presence of noise. However, the results from the current study indicate that the type of feedback influences force production shape. For instance, no feedback and grayscale feedback conditions resulted in left-tailed (peak force occurs near the end of the produced force trajectory) force pulses over practice; whereas auditory and visual feedback produced more symmetric impulses near the end of practice. These findings along with the logistic analysis are contrary to the tenets set forth in the minimum variance hypothesis. It should be noted that mean values of skewness for auditory, visual, and grayscale feedback
approached zero over practice which may have led to decreased variability in comparison to no feedback.

Several researchers have proposed that an efference copy may help the CNS calibrate proprioceptive feedback with exteroceptive feedback (Blakemore et al., 2000; Wolpert, 2007). This calibration process may aid in motor planning by reducing the error of the forthcoming response (Blakemore et al., 2000; Voss et al., 2007). In discrete force control, reports have shown that attempts to produce a criterion force level without feedback (Therrien & Balasubramaniam, 2010) have led to less accuracy than with feedback. Results from the current study extend this notion; various modes of feedback may help calibrate proprioceptive feedback. Moreover, the mechanism that sub-serves this calibration process is an individual’s ability to discriminate distinct modes of feedback.

Auditory acuity has been suggested to play a primary role during the acquisition of novel speech movements. Individuals with greater auditory discrimination create more auditory goal-directed sounds for vowel production (Ghosh et al., 2010). In the current study, auditory discriminability scores were positively associated with several force variability and accuracy measures, such as AE of peak force, SD of peak force & SD of time to peak force during the first block of 30 trials. Theoretical models on information processing in speech have proposed that learning is guided by auditory and somatosensory targets in the acquisition phase (Guenther, 2006). The current study extended this to the production force pulses produced by manual effectors. Findings from this study support the notion that auditory representations are important during the acquisition phase of a skill. Interestingly, several correlations were found between grayscale discriminability and force variability and accuracy scores. Few data about how one’s visual grayscale, contrast, or color discrimination may aid into the formation of a reference of
correctness in manual movement seem to exist in the literature. Nonetheless, the current findings suggest that grayscale acuity is another mechanism that may help discern response produced feedback from the reference of correctness.

Force production accuracy and shape improved from the first to the second blocks of practice. This finding is in line with other findings during isometric contractions (Christou et al., 2007). Changes in CNS activity have been suggested to be responsible for improvements in force production accuracy and decreases in force variability must be associated with changes in CNS activity. Hikosaka et al. (2002) suggested that initial practiced-induced adaptations in cortical centers such as prefrontal cortex, putamen, and thalamus were associated with the process of learning a new motor task explicitly, which involves spatial improvements followed by development of fine-tuned reference of correctness to further improve motor performance. The findings of the current experiment are consistent with the idea that initial practice primarily promotes improvement in the spatial characteristics of the task (Christou et al., 2007). Several trial effects were found on force production accuracy and shape, suggesting that individuals produced a symmetric impulse with feedback. This adjustment leads to an improvement in accuracy and shape regardless of the feedback; however, there were no improvements in force production shape without feedback. This adjustment in force control may be associated with increased activation of the putamen, which was previously implicated during initial learning (Floyer-Lea & Matthews, 2005)

In summary, the findings from Experiment 1 revealed four interesting findings on force production shape and accuracy, and provided novel results contrary to the minimum variance hypothesis. First, sensory feedback improved accuracy and shape of the force pulse and that auditory feedback may provide more temporal information. These results suggest that sensory
feedback plays a fundamental role in planning the motor command. Second, participants tend to produce a non-symmetric impulse early during practice and the non-symmetric/symmetric characteristics depend on the type of sensory feedback. Third, higher levels of auditory and grayscale discriminability were associated with higher levels of accuracy and reduced variability suggesting that the use of these sources of feedback to calibrate exteroceptive feedback to a template or references of correctness may be dependent on discrimination ability. Fourth, practice reduces force production variability with or without extrinsic feedback; however, practice does not help produce a more symmetric shape without feedback. The findings from Experiment 1 provide insight on how the CNS adapts during practice to various forms of feedback. Feedback serves as a facilitator in the production of an impulse shape and is used to reduce force variability.
4. 1. ARE AGE-RELATED DIFFERENCES IN FORCE PRODUCTION ACCURACY AND SHAPE MEDIATED BY SENSORY FEEDBACK ACROSS EFFECTORS?

Sensorimotor control is reduced in elderly adults. It is a common finding that older adults are slower and more variable in their motor responses (Christou & Carlton, 2002; Poston et al., 2008b). Age-related differences in rapid movements have been suggested to be in part due to central processing deficits (Cerella, 1990). These age-related differences are not consistently found across limbs and are reduced over extended practice, strength training, or other psychometric activities. As a result, many mechanisms are believed to be altered or impacted due to the aging processes (Enoka et al., 2003). One factor that may influence age-related differences in force control is the integration of sensory feedback.

The right hemisphere hypothesis of aging suggests older adults are more variable in visuo-spatial tasks than auditory-related tasks (Golderstein & Shelly, 1981). Sensory modality differences may result from differential reliance of auditory and visual systems on attention (Coull et al., 2001). Visual feedback processing relies on the ability to discern and correct visuo-spatial information. Auditory processing is equipped with powerful inhibitory capacities. It should be noted that older adults have been shown to have a reduced ability to inhibit their motor responses (e.g., Lustig, May, & Hasher, 2001). The right-hemisphere model of aging has been supported in tasks that involve speech-specific motor tasks and manual limb tasks (see Dolcos, Rice, & Cabeza; 2002 for a review); however, there is evidence to suggest that a more general motor impairment exists (Poston, Enoka, Enoka, 2008a). Poston et al. (2008a) had younger and older individuals produce force pulses with their left and right hand. The authors found age-
related differences in force control; however, there were no differences in force control between the right and left hand in older adults. Notably, new investigations have suggested that lateralization of cortical networks in discrete and continuous force control tasks in younger adults exists (Neely, Coombes, Planetta, & Vaillancourt, 2011). Neely et al. (2001) found that unique blood-oxygen-level-dependent (BOLD) activity was uniquely found in right hemisphere regions for continuous force tasks and left hemisphere regions for discrete force tasks. According to the right-hemisphere model of aging, continuous force control tasks should result in greater age-related differences in force control. Contrarily, previous work by Christou & Carlton (2001) has shown that age-related differences in force control are greater in discrete force tasks; whereas no differences were found in continuous force tasks. A mediating factor that furthers the discussion on age-related differences in continuous force tasks is how the sensory feedback is presented (Ofori et al., 2010)

Reports have shown that older adults are more variable in discrete force control tasks (Christou & Carlton, 2001). This age-related decrement in force control is exacerbated early in practice/training in discrete force control tasks (Christou et al., 2007). Older adults may have difficulty adjusting force-time requirements needed for precise force control. Christou et al. (2007) have shown that older adults have difficulty tuning the required agonist/antagonist co-contraction strategies.

An ongoing discussion in aging and motor control is whether age-related differences in task performance are exacerbated by central or peripheral mechanisms. Rapid limb movements seem more difficult for older adults because of the multiple factors that must be controlled which usually results in increased task variability. In isometric motor tasks, this age-related decline is found especially at low force levels. This may be due to the finding that older adults have a
reduced distribution of motor units. Other skeletal muscle-related properties seem to decline as an individual grows older. For example, spatial discrimination on the lip surface has been demonstrated to be less effective in older adults when compared to younger adults (Schneider, Diamond, Markham, 1986). Moreover, older adults have been shown to have problems with spatiotemporal organization of speech movements (Wohlert & Smith, 1998). Post-trial feedback from rapid movements may aid the neuromuscular system’s ability to produce an effective response (see Discussion Experiment 1). Thus, examining variability in producing rapid force pulses under various sensory feedback modalities across oral and limb effectors may help better explain specific neuromuscular issues related to decrements in force control.

As such, the purpose of Experiment 2 was to examine oral and manual force control in younger and older adults using post-trial auditory and visual feedback. By presenting post-trial sensory feedback via visual and auditory modalities, an indication of the control strategies used to integrate sensory feedback for accurate force pulse performance can be obtained. Older adults should have increased force variability and reduced accuracy than younger adults with visual feedback across oral and manual effectors. Conversely, age-related differences in force variability should be minimized in auditory feedback conditions across oral and manual effectors.

4.2 METHOD

4.2.1. Participants

Twenty-three participants [12 younger college aged (7 female; mean = 23.5±3.3 years; range = 20-30) and 11 elderly aged (7 female; mean = 73.2±6 years; range = 65-85) individuals with no history of head, jaw, hand, shoulder, wrist, and elbow pathology or current upper extremity injuries were recruited from the University of Illinois in Urbana-Champaign and
surrounding areas. All participants reported being right hand dominant. An institutional review
board consent document was given to the participant. Each participant confirmed consent with
the experimental procedures by signature. All participants had normal hearing in the speech
frequencies (500-4000 Hz) as assessed with the GSI 16 Audiometer (Granson-Stadler, Eden
Prairie, MN). Hearing was better or equal to 20 dB at 500, 750, 1000, 2000, 3000, and 4000 Hz.
Participants did not have any recent self-reported history of neurological disorders, psychiatric
disorders, speech-language disorders or motor impairments. None of the participants had more
than one year of musical training for instruments or singing. All participants provided informed
consent.

4.2.2. Apparatus

The apparatus was similar to that used in Experiment 1 except a bite force measuring
device and chin rest were added. The individual’s head was placed in a chin rest with a forehead
bar to minimize head movements that may influence jaw force production. Once the individual
was comfortably placed into the head apparatus, a device to measure bite forces was placed into
the individual’s mouth. A strain-gauge transducer was mounted on a rigid cantilever beam
(Barlow & Netsell, 1986) that was connected to two arms forming a bite bar to holder the device
in place between the teeth of the mandible and maxilla. The bite bar was coated with Provil
Putty Fast Set Base and Catalyst (Heraceus Kulzer Inc., Armonk, NY) to form a secure pseudo-
denture that could easily be removed and did not adhere to the teeth. The voltage signal from the
bite force transducer was amplified (Bio-Communication Electronics, Madison, WI).

4.2.3. Experimental Procedures

Participants produced force with the elbow flexors and jaw elevators. The MVC was
assessed in the same manner as Experiment 1 for both effectors. The elbow flexion task was the
same as Experiment 1 except that only the visual and auditory feedback conditions were used. For lower jaw elevation, the individual was instructed to sit with their back in an erect position (See Figure 4.1). Then, the strain-gauge instrument with a bite-force block was placed in the participant’s mouth. As with the elbow flexion task, the visual and auditory feedback conditions were used for the jaw elevation task. A peak force of 50 N was used for the criterion force level for both effectors and 70 trials were performed at each unique condition. A total of 280 trials were performed.

**Figure 4.1 Force transducer used to measure jaw elevation (TOP). Sagittal view of the participant with the jaw force transducer (BOTTOM).**
4.2.4. Data Analysis

Data analysis was similar to Experiment 1. A 2 x 2 x 2 mixed model repeated measures ANOVA was conducted. The between group factor was age (younger and older) and the within factors were feedback (visual and auditory) and effector (elbow and jaw). The dependent variables computed were the same as Experiment 1. No gender effects were performed due to the small sample of male and female participants. Data were acquired and analyzed using LabView 2011 software (National Instruments, Austin, TX).

4.3. RESULTS

Maximal strength was assessed to get an indication of the participant’s maximal force production capabilities (See Figure 4.2). Older adults (135.6 N) produced less maximal force a younger adults (184.7 N) \[F(1,21) = 7.45, p<0.05\]. The elbow (122.2 N) had less maximal force than the jaw (198.0 N) \[F(1,21) = 32.4, p<0.05\].

Figure 4.2 Average MVC as a function of age and effector.

Effector Strength

![Figure 4.2 Average MVC as a function of age and effector.](image-url)
4.3.1 Force Production Accuracy

Mean peak force provides an indication of the whether participants produced the criterion peak force level. Mean peak force was influenced by effector \([F(1,21) = 19.1, p<0.05]\) and there was an effector x feedback interaction \([F(1,21) = 11.3, p<0.05]\) (see Figure 4.3). On average, participants approximated the criterion peak force with the elbow but significantly overshot with the jaw. Post hoc analysis revealed that the effector x feedback interaction resulted from similar mean peak force in auditory and visual conditions of the elbow; but greater mean peak force in the visual conditions than the auditory feedback conditions of the jaw.

Absolute error of peak force was influenced by effector \([F(1,21) = 16.2, p<0.05]\), feedback \([F(1,21) = 4.79, p<0.05]\), and there was an effector by feedback interaction \([F(1,21) = 9.9, p<0.05]\). The interaction effect resulted from greater AE in the visual conditions than the auditory conditions for the jaw; whereas, there was less AE in the visual conditions than the auditory conditions for the elbow (see Figure 4.4). There was no effect of age on absolute error \([F(1,21) = 1.8, p>0.05]\).

In general, older adults were more variable in peak force production and this finding was mediated by feedback. Age \([F(1,21) = 10.7, p<0.05]\), feedback \([F(1,21) = 4.15, p<0.05]\), and effector \([F(1,21) = 42.5, p<0.05]\) were found to influence SD of peak force (see Figure 4.5). Lower SD was found in younger (11.8 N) than older adults (17.4 N); with auditory feedback (13.7 N) than visual feedback conditions (15.5 N); and with the elbow (9.2 N) than the jaw (20.1 N). For the CV of peak force, there was a significant effect of age \([F(1,21) = 4.91, p<0.05]\), effector \([F(1,21) = 28.9, p<0.05]\), and there was a significant feedback x age \([F(1,21) = 28.9, p<0.05]\) interaction (see Figure 4.6). Younger adults had lower CV (0.23) than older adults (0.28). The elbow had lower CV (0.18) than the jaw (0.34). Post hoc analysis revealed the
feedback x age interaction resulted from greater CV in the visual feedback conditions (0.30) than the auditory conditions (0.27) in older adults; whereas, lower CV (0.21) was found in visual feedback conditions than auditory conditions in younger adults (0.24).

**Figure 4.3 Mean peak force as a function of feedback and effector.**
Mean time to peak force provided an indication of whether participant’s produced the criterion time to peak force (see Figure 4.7). Auditory feedback resulted in mean times to peak force closer to the criterion 200 ms than visual feedback \( F(1,21) = 6.60, p<0.05 \). Absolute error of time to peak force was influenced by age \( F(1,21) = 4.79, p<0.05 \) and effector \( F(1,21) = 5.18, p<0.05 \). Younger adults had lower AE (57 ms) than older adults (85 ms) and the elbow resulted in lower AE (60 ms) than the jaw (82 ms) (see Figure 4.8). There were no significant effects of age, feedback, or effector on SD of time to peak force. Feedback was found to
influence CV of time to peak force \([F(1,21) = 4.30, \ p<0.05]\). Auditory feedback conditions (0.29) had greater CV than visual feedback conditions (0.24) (see Figure 4.9).

**Figure 4.5 Standard deviation of peak force as a function of age, feedback, and effector.**
Figure 4.6 Coefficient of variation of peak force as a function of age and feedback.
Figure 4.7 Mean time to peak force as a function of feedback.
Figure 4.8 Absolute error of time to peak force as a function of feedback.

Mean squared error provides a general indication of force production accuracy. Mean squared error was influenced by effector \([F(1,21) = 6.144, p<0.05]\) but the main effects of age and feedback were not significant. There was an interaction between feedback and effector \([F(1,21) = 5.69, p<0.05]\). Mean squared error for the elbow was lower with visual feedback; whereas, MSE for the jaw was lower with auditory feedback (see Figure 4.10).
Figure 4.9 Coefficient of variation of time to peak force as a function of feedback

![Coefficient of variation of time to peak force as a function of feedback](image)

Figure 4.10 Mean squared error of force production as a function of feedback and effector.

![Mean squared error of force production as a function of feedback and effector](image)
Mean impulse provides an indication of the aggregate force over time. Age \([F(1, 21) = 10.67, p<0.05]\) and feedback \([F(1, 21) = 4.64, p<0.05]\) influenced mean impulse (see Figure 4.11). Younger adults produced a smaller impulse (11.8 Ns) than older adults (16.4 Ns). Auditory feedback (13.2 Ns) resulted in smaller impulses than the visual feedback (15.0 Ns). Statistical analysis revealed an age \([F(1, 21) = 13.70, p<0.05]\), effector \([F(1, 21) = 13.40, p<0.05]\), and effector x feedback interaction \([F(1, 21) = 13.63, p<0.05]\) on SD of impulse (see Figure 4.12). Younger adults (3.2 Ns) were less variable than the older adults (5.7 Ns). The effector x feedback interaction resulted from greater SD with auditory (3.7 Ns) than visual feedback (3.4 Ns) for the elbow, whereas lower SD was found for auditory feedback (4.5 Ns) than for visual feedback (6.2 Ns) for the jaw. There were no age, feedback, or effector effects on CV of impulse.

**Figure 4.11 Mean impulse as a function of age and feedback.**
4.3.2 Force Production Shape Characteristics

Mean skewness provides a general indication of whether participants produced a symmetric force pulse (see Figure 4.13). Effector \([F(1,21) = 6.2, p<0.05]\) and an age \(\times\) effector interaction \([F(1,21) = 4.54, p<0.05]\) were found to influence mean skewness. Post hoc analysis revealed that the interaction resulted from similar degrees of skewness for the elbow (-0.21) and the jaw (-0.22) for older adults; whereas, there was greater skewness in the jaw (-0.26) than the elbow (-0.08) for younger adults.
Mean kurtosis provided an indication of the peakedness of the force pulse (see Figure 4.14). There were greater mean kurtosis values in the jaw than the elbow \[F(1,21) = 15.5, p<0.05\]. There were no significant effects of age and feedback.

The logistic function provided an indication of whether the force pulse produced matched a Gaussian function. The logistic function was fit to each unique trial and an adjusted r-square value was computed. Analysis of the adjusted r-square values indicated a significant effect of age \[F(1,21) = 7.4, p<0.05\] and effector \[F(1,21) = 8.7, p<0.05\]; however, there was no effect of feedback on adjusted r-square values. Younger adults (0.89) had a greater adjusted r-
square value than older adults (0.74) and the r-square value for the elbow (0.94) was greater than the jaw (0.67).

**Figure 4.14 Mean kurtosis of the force trajectory as a function of effector.**

![Bar chart showing mean kurtosis for elbow and jaw](chart.png)

Mean inflection point of the logistic function provided a means to assess the symmetry of the force pulse. Age [F(1,21) = 11.8, p<0.05] and feedback [F(1,21) = 6.5, p<0.05] were found to influence mean inflection point. Younger adults had lower means (148 ms) than older adults (192 ms). Auditory feedback had lower means (163 ms) than the visual feedback (177 ms) (see Table 4.1). Older adults (39 ms) produced greater SD of inflection point than younger adults (28 ms) [F(1,21) = 7.4, p<0.05]. Coefficient of variation of the inflection point provides an indication of the variability of scaling a symmetric impulse. Lower values indicated more symmetric impulses, whereas, higher values indicated non-symmetric impulses. Effector [F(1,21) = 28.25, p<0.05] and feedback [F(1,21) = 5.52, p<0.05] were found to influence the CV.
of the inflection point. There was less CV in the elbow (0.17) than the jaw (0.23). The feedback effect resulted in greater CV in the auditory (0.21) than visual conditions (0.19) (see Figure 4.15).

**Figure 4.15** The goodness of fit across age and effector for the Gaussian function.
Table 4.1. Mean inflection point as a function of age, feedback, and effector

<table>
<thead>
<tr>
<th>Feedback</th>
<th>Effector</th>
<th>Group</th>
<th>Group</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Younger</td>
<td>Older</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Auditory</td>
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</tr>
<tr>
<td></td>
<td>Elbow</td>
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</tr>
<tr>
<td></td>
<td>Jaw</td>
<td>122</td>
<td>177</td>
</tr>
<tr>
<td>Visual</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Elbow</td>
<td>162</td>
<td>204</td>
</tr>
<tr>
<td></td>
<td>Jaw</td>
<td>143</td>
<td>197</td>
</tr>
</tbody>
</table>

*p < .05, **p<.01

4.3.3 Feedback Discriminability and Force Production Accuracy

Table 4.2 indicates the average sensory discrimination scores from all participants. These results are reported to give a sense of individuals range in perception. Pearson correlations were computed between discriminability scores and the impulse and force dependent measures (see Table 4.3). Statistical analysis revealed significant correlations between participant’s auditory discriminability scores and mean AE of peak force in the elbow ($r=0.69$), SD of time to peak force in the jaw ($r=0.47$), CV of time to peak force in the jaw ($r=0.42$), SD of impulse in the jaw ($r=0.43$), and AE of mean time to peak force in the jaw ($r=0.65$).

Statistical analysis revealed significant correlations between participant’s visual discriminability scores and SD of the impulse in the elbow ($r=-0.38$) and mean AE of time to peak force in the jaw ($r=-0.41$).
Figure 4.16 Coefficient of variation as a function of feedback and effector

Table 4.2 Discrimination scores from Sensory Tests of Experiment 2

<table>
<thead>
<tr>
<th>Sensory Test</th>
<th>Mean</th>
<th>SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Auditory (Hz)</td>
<td>13.80</td>
<td>11.10</td>
</tr>
<tr>
<td>Visual (mR)</td>
<td>0.38</td>
<td>0.19</td>
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</table>
Table 4.3 Correlations between Discriminability Tests and Experimental Conditions

<table>
<thead>
<tr>
<th>Dependent Variable</th>
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<th>Visual</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Elbow</td>
<td>Jaw</td>
<td>Elbow</td>
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<tr>
<td>Sensory Test</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>AE of Peak Force</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Auditory</td>
<td>0.69**</td>
<td>-0.10</td>
<td>-</td>
</tr>
<tr>
<td>Visual</td>
<td>-</td>
<td>-</td>
<td>0.01</td>
</tr>
<tr>
<td>AE of Time to Peak Force</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Auditory’</td>
<td>-0.20</td>
<td>0.65*</td>
<td>-</td>
</tr>
<tr>
<td>Visual</td>
<td>-</td>
<td>-</td>
<td>-0.21</td>
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<tr>
<td>SD of Time to Peak Force</td>
<td></td>
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<td></td>
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<tr>
<td>Auditory</td>
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<td>Visual</td>
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<td>-</td>
<td>0.07</td>
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<tr>
<td>SD of Impulse</td>
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<td></td>
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</tr>
<tr>
<td>Visual</td>
<td>-</td>
<td>-</td>
<td>-0.38*</td>
</tr>
</tbody>
</table>

*p < .05, **p<.01

4.4. DISCUSSION

The purpose of Experiment 2 was to examine how feedback influences age-related and effector differences in discrete force production. Older adults are typically more variable and slower in their force production in comparison to younger adults. It is suggested that this decrement in force production accuracy is mediated by visual feedback. It is well known that visual feedback is the typical feedback provided for manual control and that auditory feedback is the typical feedback provided for oral effectors. However, it is not clear how auditory and visual
feedback influence force production accuracy, variability, and shape across effectors for younger and older adults. Auditory and visual feedback were examined across the elbow and jaw for younger and older adults. Older adults were hypothesized to have less force production accuracy than younger adults with visual feedback across oral and manual effectors and that the age-differences would be reduced with auditory feedback. The jaw was expected to be more variable than the elbow.

In general, the results from Experiment 2 supported these hypotheses. Older adults had lower force production accuracy, greater force variability, and were more variable in producing a consistent shape. As hypothesized, an age x feedback interaction on CV of peak force was found indicating that age-related differences in force production are mediated by visual feedback. Auditory feedback also resulted in greater accuracy and lower variability than in the jaw; whereas visual feedback resulted in greater accuracy and lower variability in the elbow. This was highlighted by effector x feedback interactions for AE of peak force, MSE, and SD of impulse. Interestingly, there were minimal effector differences with auditory feedback. An age x effector interaction on skewness of the force pulse resulted from older adults producing the same stereotypical non-symmetric impulse across effectors; whereas, younger adults produced a more symmetric impulse in the elbow. Several significant correlations were identified between auditory discriminability scores and jaw feedback conditions after acquisition, which would support the notion that auditory acuity plays a fundamental role in the formation of accurate force shapes. Taken together, the results indicated that feedback is essential in characterizing age-related and effector differences in force production shape and accuracy. Moreover, visual feedback may play a differential role across oral and manual effectors.
One of the tenets of the right hemisphere hypothesis of aging proposes that older adults experience a non-symmetrical decline in the right hemisphere, which impairs visuospatial processing in motor tasks. The findings from the current study support this notion. An age x feedback interaction on the CV of peak force was found, which resulted from minimal age-related differences in force variability for auditory feedback compared to visual feedback. One explanation may be that the inhibitory characteristics of auditory feedback may provide information that allows older adults to scale an appropriate force shape for task performance. Auditory processing is equipped with powerful inhibitory capacities. Older adults have been shown to have a reduced ability to inhibit their motor responses (e.g., Lustig, May, & Hasher, 2001; Teeken et al., 1996). Auditory feedback may have provided more sensory information to reduce unwanted force responses.

The loss of adaptability hypothesis indicates that the complexity of older adults motor output depends on the nature of the tasks and dynamics of the motor system (Vaillancourt & Newell, 2003). In the current study, older adults were unable to produce symmetric force pulses with the elbow in comparison to younger adults. This finding may be related to older adults’ inability to fine tune the proper feedback needed to select the appropriate motor command across effectors (see Discussion Experiment 1). There was a discrepancy in the skewness results of Experiment 1 and Experiment 2. In Experiment 1, skewness values were positive after initial practice while in Experiment 2 skewness values for the elbow were negative. These findings may stem from the different force levels used across experiments. Lower force levels may lead to more left-tailed impulses; whereas, higher force levels lead to more right-tailed impulses. This may explain the minimal association between high and low levels of discrete force variability (Ofori, Sosnoff, & Carlton, 2012).
The defining feature of the logistic curve is that growth is distributed equally before and after the inflection point. That is, there is symmetry to the growth pattern such that exactly half of the total change has occurred before the inflection point. The findings from the current study suggest that the jaw selects a non-symmetric curve in order to accomplish task demands. This finding contradicts tenets proposed by the minimum variance hypothesis. Younger adults produced a more non-symmetric impulse that led to similar accuracy in comparison to the elbow (see results on AE of peak force and MSE), this would suggest that a symmetric impulse may not be the optimal impulse needed for minimal variability as stated in other theories of impulse shape production (e.g., Gordon & Ghez, 1987; Harris & Wolpert, 1998; Meyer et al., 1982; Schmidt et al., 1979).

As expected based on the results from Experiment 1, auditory acuity was found to play a role in determining one’s variability. Interestingly, most of the correlations found between the feedback discriminability and force accuracy measures were for the jaw not the elbow. In the current experiment, auditory discriminability scores were moderately associated with several force variability and accuracy measures, such as AE of peak force, SD of peak force & SD of time to peak force. This was after the acquisition phase; contrary to speech information processing models that suggest auditory acuity plays a predominant role during acquisition. Thus the current findings suggest one of two possibilities. The jaw may not have accurately learned the required template to scale a symmetric impulse; however, this may not be plausible as no differences were found between the elbow and jaw error scores. Another explanation may be that auditory acuity plays a fundamental role in planning the motor command and that the jaw may be over-reliant on sensory feedback. This later explanation may somewhat reconcile the stark differences in force variability between the elbow and jaw. It should be noted that jaw
closing muscles are not readily used in speech, thus the integration of sensory feedback may be reduced for these effectors.

In summary, the findings from Experiment 2 indicated that age-related differences in force variability are dependent on sensory feedback. Findings from Experiment 1 that the type of sensory feedback influenced temporal measures of force production were extended. Visual feedback resulted in greater force variability and less accuracy in the jaw; whereas, auditory feedback resulted in greater force variability and less accuracy in the elbow. Oral and jaw effectors were shown to produce distinct force pulse shapes.
CHAPTER 5
DISCUSSION

The purpose of this dissertation was to examine the fundamental role feedback plays in force production accuracy, variability, and shape and how the role of feedback varies across effectors and age. In Experiment 1, the premise of several impulse variability theories (e.g., Schmidt et al., 1979; Harris & Wolpert, 1998), that suggest that force variability is primarily due to the limitations of the neuromuscular system, were tested. These theories suggest that increases in the required level of force production leads to increases in force variability. The main culprit for this observation is neuromotor noise. Moreover, there is an ongoing discussion of how individuals adapt force pulses to minimize force variability. Schmidt et al. (1979) modeled the force-time function as a rectangular shape. The rectangular impulse shape was used to easily make predictions about variability in movement tasks. Harris & Wolpert (1998) suggest a symmetric impulse is produced in order to minimize force variability in the presence of noise. Gordon and Ghez (1987) suggest the shape of the impulse is dependent on the time constraints of the impulse. The impulse is more peaked in rapid conditions and less peaked in the presence of feedback. Thus, Gordon and Ghez suggest the shape of the impulse depends on the task requirements. These force impulse theories make little reference to the formation of a reference of correctness. This reference of correctness may be formed through the exteroceptive feedback provided after the force pulse is produced. If force variability is directly related to the muscular impulse, force variability should be independent of feedback.

The results from Experiment 1 & 2 suggest that variability in the time of peak force depended on sensory feedback. Sensory feedback also aided the formation of a symmetric force pulse. Individuals had greater force variability and skewed force pulses without feedback.
Individuals were not able to adapt a symmetric impulse over practice without feedback. The results from Experiment 1 & 2 suggest that participants adapt non-symmetric force pulses over practice and sensory feedback is associated with accurate and consistent discrete force production.

Sensory feedback and its influence on force variability have many practical and theoretical implications in movement control. From a practical perspective, variability provides an indication of skill, as it represents the stability of a given movement. Feedback may be a facilitator for an individual to adapt a symmetric force pulse. From a theoretical perspective, one might consider variability as a consequence of a faulty control processes in the sensorimotor system (e.g., Schmidt et al., 1979). Feedback may serve as an aid to help minimize the errors or regulate the faulty control processes. Nonetheless, the results from this dissertation suggest that feedback plays a fundamental role in the production of accurate and consistent force pulses across the lifespan.

FORCE CONTROL AND FEEDBACK DISCRIMINABILITY

The ability of individuals to perceive small differences in the motor domain has been a topic of inquiry for over a century (e.g., Fullerton & Cattell, 1892). The ability of individuals to discriminate between force levels has served as a window into the nature of control processes governing movement. Fullerton & Cattell (1892) employed a just noticeable difference (JND) method with the assumption the smaller the JND the greater the fineness of discrimination. The JND represents the minimal change in stimulus intensity that produces a noticeable discrepancy in one’s perceptual experience and is related to a number of factors including stimulus intensity and sensory modality. However, the findings of Fullerton & Cattell were not in line with
Weber’s Law which states that the sensation is directly proportional to stimulus intensity but that these changes in JND occur logarithmically with increases in force level.

The encoding of sensory parameters may depend on the type of sensory stimulus. For example, visual and auditory feedback modalities have different properties and sensation structures. Auditory feedback has a tonotopic organization and most of its encoding occurs in the periphery (e.g., cochlea); whereas, visual feedback has a retinotopic organization and most of its encoding occurs in subcortical structures (e.g., lateral geniculate nucleus). It has been shown that auditory feedback uses a highly organized gain control mechanism that processes simple sounds (e.g., pure tones) in the peripheral processing sites (e.g. cochlea). In the current experiments, auditory feedback was presented as a pure tone. The sensory discrimination test for audition was an adaptive pitch test, in which participants were forced to choose if the second of two presented tones was higher or lower than the first tone. In the first trial block from Experiment 1, and the jaw auditory condition in Experiment 2, sensory discrimination with audition was positively correlated with measures of force production accuracy (e.g., AE of peak force, MSE) and force variability (e.g., SD of peak force, and SD of time to peak force). This suggests that auditory discrimination aids in the formation of a reference of correctness. There have been several models proposed to describe how individuals discriminate differences in pitches (Cohen et al., 1995; Micheyl, Ryan, & Oxenham, 2012). Although the exact pitch model used by participants is beyond the scope of this study, nonetheless the correlational findings from the current dissertation suggest that individuals use a pitch mechanism to develop a reference of correctness for rapid force production. A pitch gain control mechanism plays a role in influencing force production across effectors.
It is well established that retinal luminance affects the spatial and temporal summation properties of the visual system (Rovamo et al., 1999). It is hypothesized that retina cells with different contrast tuning are needed to process visible contrast domain and form several contrast channels, such as spatial frequency or contrast channels (e.g., Crowder et al., 2009). Contrast is the distance of luminance values between two colors. For instance, in the current experiment white represented a value of 255; whereas, black represented a value of 0. It is proposed that these selective contrast channels are responsible for changes in contrast perception. These contrast channels are suggested to be due to the relative properties of the magnocellular and parvocellular pathways in the brain. Parvocellular pathways are suggested to respond best to stimuli with high contrast, high spatial frequency and low temporal frequency. Conversely, magnocellular cells are sensitive to a wide range of contrasts including strong neural responses to low contrasts (Shapley, 1990), low spatial frequencies and high temporal frequencies.

In the Experiment 1, grayscale discrimination scores were correlated with MSE of the force pulse for the second and third trial blocks. Moreover, the average force pulse duration was approximately 400 ms, leading to a 2.5 Hz temporal frequency. Perhaps, over practice, participant’s retina cells adapted to spatial and temporal properties afforded by grayscale feedback. In a study conducted by Solomon, Pierce, Dhruv and Lennie (2004), the authors indicated that monkey magnocellular cells have a contrast adaption at a subcortical level. Although the behavioral nature of this study limits the exact contrast adaption channel or model used to discriminate the grayscale feedback, it is suggested that this contrast mechanism is used to develop a reference of correctness for rapid force production. Taken together, adjustments to the spatial and temporal properties of matching force production to a criterion are in part related to one’s ability to discriminate sensory information.
EFFECTOR DIFFERENCES BETWEEN THE ELBOW AND JAW

While it is well established that muscular force pulses play a fundamental role governing the spatial trajectory of a limb, it is unclear how this relates in the governing of oral motor force pulses. Skilled movement is a result of a coordination of multiple levels of the nervous system to act as a unified unit regardless if the movement is produced by the limbs in tasks such as grasping, striking, or kicking or by the oral effectors such as chewing, sucking, and singing.

There is evidence to suggest that a common timing control process is involved in oral and motor effectors (Franz, Zelaznik, & Smith, 1992). The authors had participants produce tapping and repetitive movements with their finger, arm, and jaw; and found significant correlations between effectors. Although the main purpose of Franz et al. (1992) was to test the notion of a common timing mechanism across effectors, the authors reported intertap interval variability (i.e., SD) of the each effector. The jaw (13.43ms) was found to be almost 4 times more variable than the arm (3.78 ms)! Reports that have tested several impulse variability theories suggest that the level of peak force variability is a result of the time to peak force and level of peak force (Carlton et al., 1993; Sherwood, 1986). Based on these reports, one would predict that the jaw and elbow produce different impulses and different force pulse shapes. However, this prediction has not been tested with the oral motor effectors. Distinct oral musculature and speech production muscles govern the opening and closing of the oral articulators (Gracco, 1990). As such, it would seem plausible that the sensorimotor system would adapt greater skewed impulses in the closure or opening of the oral articulators. Reports have suggested that the oral articulators produce non-symmetric velocity curves in comparison to manual effectors (Ostry, Cooke, & Munhall, 1987). Results from Experiment 2 extend these findings. In Experiment 2, the jaw effectors produced greater peaked and skewed force pulses in comparison to the elbow.
effectors. This provides more evidence for the notion that the sensorimotor system adopts non-symmetric force pulses and the symmetry/non-symmetry of the force pulse is dependent on the effector, feedback, and individual.

There are several explanations for the effector differences found on discrete force production accuracy, variability, and shape measures. In Experiment 2, the jaw had similar force production accuracy in comparison to the elbow in younger adults; however, the jaw was more variable in peak force and there was less symmetry in comparison to the elbow. These differences may be due to biomechanical, neural control, and gravity loading differences between the elbow and jaw. It has been shown that the oral articulators are interdependent (Gracco & Abbs, 1985) and this may also cause differences between the elbow and jaw.

The shape of the force pulse may be influenced by the various anatomical, histochemical, and physiological differences between the elbow and jaw. These differences include muscle architecture, motor unit properties, reflex organization, and differences in central neural localization (Abbink et al., 1999). In a study conducted by Abbink et al. (2001), jaw closing muscles produced more non-symmetric EMG responses to external loads than the elbow flexors. Jaw closing muscles also tended to overcome loading through sensory-induced muscle responses instead of preprogrammed responses as with the elbow flexors. In Experiment 2 of the current study, greater skewness was found in the jaw than the elbow. The jaw was also more variable in peak force and impulse. This observation suggests that the jaw relies on feedback to regulate loads which is consistent with the masseter’s abundance of muscle spindles. This may be due to the functional nature of the jaw closing muscles in its role in overcoming resistance forces while chewing.
The possibility that the physical influence of gravitational loading accounts for the difference between force production accuracy and shape between the elbow and jaw is addressed by findings on the kinematic pattern of laryngeal adduction gestures in speech (Atkeson & Hollerbach, 1985). Laryngeal adductions, like the elbow movements of this study, are primarily in the horizontal plane and not subject to the influence of gravity; whereas, the jaw elevation task was always under the influence of gravity. This may have caused the participants to produce faster rates to compensate for the effect of gravity leading to greater force variability and more asymmetry force shapes in comparison the elbow.

Another factor that may contribute to the differences in force production accuracy and shape between the elbow flexors and the jaw closing muscles may be due to the role of antagonist muscles. Ghez & Gordon (1987) demonstrated a strong association between the force trajectory and the level of EMG activity of the antagonist muscles. The faster the rate of force production the greater the level of activity of the antagonist muscle was observed for the elbow. Antagonist activity increased after peak rate of force production. The involvement of the antagonist might play a role in the symmetry and peakedness of the force pulse. The antagonist muscles may serve as a means to flatten the force pulse or reduce the peak rate of force caused by the agonist muscle. In Experiment 2, the jaw elevators produced greater peaked and non-symmetric force pulses than the elbow flexors. It is well established that the triceps muscles play a significant role in the production of rapid force pulses for the elbow flexors (Ghez & Gordon, 1987). As seen in Experiment 2, the jaw muscles produced greater peak rates (see Appendix C) and more peaked force as measured by kurtosis. The differences in force shapes may result from the fact that the jaw opening muscles, the antagonist of the jaw closing muscles, do not contain muscle spindles. As such, this agonist-antagonist interaction may lead to the non-symmetry of
the force pulses (i.e., greater skewness). The agonist-antagonist interaction may also play a factor in the non-symmetry of a force pulse across various effectors. The symmetry of force pulses may depend on the number of muscle units recruited and the level of muscle activity in the antagonist. For the production of a symmetric force pulse, participants may need to fine tune neural activity of agonist and antagonist motor units over practice (Christou et al., 2007).

AGING AND SENSORIMOTOR PROCESSING

As expected, older adults were found to be more variable in their force output than younger adults in Experiment 2. This is congruent with other findings that older adults exhibit more variable force production (Christou et al., 2003; Christou & Carlton, 2002; Poston et al., 2008a; Sosnoff & Newell, 2006; Vaillancourt & Newell, 2003). Older adults were also more variable and less accurate in their force output in the current study. This finding is in line with the notion that older adults have a reduced ability to adapt force output to varying task demands (Vaillancourt & Newell, 2003). Younger adults produced distinct force pulse shapes with the elbow and jaw as measured by skewness of the force trajectory; however, the older adults produced similar force pulse shapes (i.e., similar skewness values) across the elbow and jaw. The findings from Experiment 2 add to the accumulating evidence there is a loss of differentiation in sensorimotor function with advanced age (Li, 2002).

A possible explanation for the loss of adaptability of older adults may be the role of the antagonist muscles. As previously mentioned, the jaw antagonists (i.e., jaw muscle openers) have no muscle spindles. Thus, the finding of similar force shapes between the elbow and jaw for older adults would suggest that older adults failed to incorporate the proper antagonist activity needed for an increase in force production accuracy, symmetric force pulse shape and decrease in force variability. Similarly, Christou et al. (2007) have proposed that older adults
have a reduced ability for adapting antagonist muscle activity to reduce force variability in the limbs.

Age-related differences in force variability found in the current study were mediated by effector and sensory feedback. It is suggested that oral effectors have a reduced ability to integrate visual information in comparison to a no feedback condition (Sowman & Türker, 2007). As such, the findings from the current experiment partly support tenets of the right-hemisphere hypothesis of aging. Age-related differences in force control were minimal with auditory and visual feedback of the elbow; whereas, the differences were more pronounced with the jaw effectors.

It should be noted that the jaw muscles produced more force and were more variable than the elbow effectors. This would be in contrast with findings that suggest that weaker muscles are more variable than larger muscles (Hamilton et al., 2004). Conversely, Christou and Carlton (2002) found that force variability was greater in the knee extensors than the elbow flexors. One discrepancy between the two findings is the task used to assess force variability. For instance, Hamilton et al. (2004) used a continuous force control task to assess force accuracy, whereas the current study used a discrete force control paradigm.

In summary, the current experiments demonstrate that sensory feedback is essential in force production accuracy, variability, and shape. Sensory feedback is essential for regulating temporal measures. Effector differences across the lifespan may be due to the ability to integrate sensory feedback. Taken together, the findings from this study support the notion that force production accuracy, variability, and shape may be a result of the individual, task, and the environment (Newell, 1985).
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   Kinematic analyses of autogenic and nonautogenic sensorimotor processes. *Journal of Neurophysiology, 54*(2), 418-432.


   *Journal of Communication Disorders, 39*(5), 350-365


APPENDIX A: ALL EXPERIMENTAL DATA PRESENTED IN FIGURES FROM
EXPERIMENT 1
Figure A.1 Average MVC of each Experimental condition across participants.
Figure A.2 Mean peak force from each feedback condition across trial blocks.
Figure A.3 Mean absolute error of peak force from each feedback condition across trial blocks.
Figure A.4. Standard deviation of peak force from each feedback condition across trial blocks.
Figure A.5. Coefficient of variation of peak force from each feedback condition across trial blocks.
Figure A.6 Mean times to peak force from each feedback condition across trial blocks.
Figure A.7 Mean absolute error of time to peak force from each feedback condition across trial blocks.
Figure A.8 Standard deviation of time to peak force from each feedback condition across trial blocks.
Figure A.9 Coefficient of variation of time to peak force from each feedback condition across trial blocks.
Figure A.10 Mean impulse from each feedback condition across trial blocks.
Figure A.11 Standard deviation of impulse from each feedback condition across trial blocks.

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<tr>
<td>2</td>
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</tr>
<tr>
<td>3</td>
<td>Auditory</td>
</tr>
<tr>
<td></td>
<td>Visual</td>
</tr>
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</table>
Figure A.12 Coefficient of variation of impulse from each feedback condition across trial blocks
Figure A.13 Mean peak rate from each feedback condition across trial blocks.
Figure A.14 Standard deviation of peak rate from each feedback condition across trial blocks.
Figure A.15 Coefficient of variation of peak rate from each feedback condition across trial blocks.
Figure A.16 Average skewness from each feedback condition across trial blocks.
Figure A.17 Average kurtosis from each feedback condition across trial blocks.

![Graph showing average kurtosis across trial blocks for different feedback conditions.](graph.png)
Figure A.18 Average integrated force pulse over time from each feedback condition.
Table A.1. Mean Inflection Point across feedback conditions

<table>
<thead>
<tr>
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<th>Block 2</th>
<th>Block 3</th>
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<tr>
<td>Visual</td>
<td>174</td>
<td>170</td>
<td>167</td>
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*p < .05, **p < .01
Figure A.19 Standard deviation of the inflection point.
Figure A.20 Coefficient of variation of the inflection point.
APPENDIX B: CORRELATIONS BETWEEN FORCE PRODUCTION ACCURACY, VARIABILITY AND SENSORY DISCRIMINATION FROM EXPERIMENT 1
Table B.1 Correlations between Mean Absolute Error of Peak Force and Discriminability Scores

<table>
<thead>
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<th>Block 2</th>
<th>Block 3</th>
</tr>
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<td>0.27</td>
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<td>-0.20</td>
</tr>
</tbody>
</table>

*p < .05, **p < .01
Table B.2 Correlations between Mean absolute error of time to peak force and discriminability scores

<table>
<thead>
<tr>
<th>Feedback</th>
<th>Condition</th>
<th>Block 1</th>
<th>Block 2</th>
<th>Block 3</th>
</tr>
</thead>
<tbody>
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<td></td>
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<tr>
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*p < .05, **p<.01
Table B.3 Correlations between Mean Squared Error of impulse and discriminability scores

<table>
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<td>0.59*</td>
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<td>Visual</td>
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<td>0.26</td>
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*p < .05, **p< .01
Table B.4 Correlations between SD of peak force and discriminability scores

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<th>Condition</th>
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<th>Block 2</th>
<th>Block 3</th>
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*p < .05, **p<.01
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<td></td>
<td>Visual</td>
<td>-0.11</td>
<td>0.22</td>
<td>-0.23</td>
</tr>
</tbody>
</table>

*p < .05, **p<.01
## Table B.6 Correlations between CV of time to peak force and discriminability scores

<table>
<thead>
<tr>
<th>Feedback</th>
<th>Condition</th>
<th>Block 1</th>
<th>Block 2</th>
<th>Block 3</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Grayscale</td>
<td>-0.16</td>
<td>0.60**</td>
<td>-0.01</td>
</tr>
<tr>
<td></td>
<td>Auditory</td>
<td>-0.11</td>
<td>-0.20</td>
<td>-0.26</td>
</tr>
<tr>
<td></td>
<td>Visual</td>
<td>0.18</td>
<td>0.07</td>
<td>0.02</td>
</tr>
</tbody>
</table>

*p < .05, **p < .01
Table B.7 Correlations between CV of impulse and discriminability scores

<table>
<thead>
<tr>
<th>Feedback</th>
<th>Condition</th>
<th>Block 1</th>
<th>Block 2</th>
<th>Block 3</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Grayscale</td>
<td>0.27</td>
<td>0.43*</td>
<td>0.07</td>
</tr>
<tr>
<td></td>
<td>Auditory</td>
<td>0.33</td>
<td>0.02</td>
<td>-0.01</td>
</tr>
<tr>
<td></td>
<td>Visual</td>
<td>0.21</td>
<td>0.05</td>
<td>-0.10</td>
</tr>
</tbody>
</table>

*p < .05, **p < .01
Table B.8 Correlations between mean inflection point times to peak force and discriminability scores

<table>
<thead>
<tr>
<th>Feedback</th>
<th>Block 1</th>
<th>Block 2</th>
<th>Block 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grayscale</td>
<td>-0.44*</td>
<td>-0.29</td>
<td>-0.42*</td>
</tr>
<tr>
<td>Auditory</td>
<td>0.00</td>
<td>0.13</td>
<td>0.10</td>
</tr>
<tr>
<td>Visual</td>
<td>-0.30</td>
<td>-0.22</td>
<td>-0.19</td>
</tr>
</tbody>
</table>

*p < .05, **p<.01
Table B.9 Correlations between CV of inflection point and discriminability scores

<table>
<thead>
<tr>
<th>Feedback</th>
<th>Condition</th>
<th>Block 1</th>
<th>Block 2</th>
<th>Block 3</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Grayscale</td>
<td>0.28</td>
<td>0.21</td>
<td>0.06</td>
</tr>
<tr>
<td></td>
<td>Auditory</td>
<td>0.57*</td>
<td>0.17</td>
<td>0.20</td>
</tr>
<tr>
<td></td>
<td>Visual</td>
<td>-0.25</td>
<td>0.17</td>
<td>0.02</td>
</tr>
</tbody>
</table>

*p < .05  **p < .01
APPENDIX C: ALL EXPERIMENTAL DATA PRESENTED IN FIGURES FROM EXPERIMENT 2
Figure C.1 Average MVC across younger and older adults in the elbow and jaw.

<table>
<thead>
<tr>
<th>Effector Strength</th>
<th>Age</th>
<th>Young</th>
<th>Old</th>
</tr>
</thead>
<tbody>
<tr>
<td>MVC (N)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>50</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>100</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>150</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>200</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>250</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>300</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- Elbow
- Jaw
Figure C.2 The criterion template and the mean produced force trajectory for each effector by feedback condition.
Figure C.3 Absolute error of peak force (Top) and time to peak force (Bottom) as a function of age, feedback, and effector.
Figure C.4 Mean squared error as a function of age, feedback, and effector.
Figure C.5 Average mean (TOP) and SD (BOTTOM) of impulse in visual and auditory feedback conditions across younger and older adults in the elbow and jaw.
Figure C.6 CV of impulse in visual and auditory feedback conditions across younger and older adults in the elbow and jaw.
Figure C.7 Mean (TOP) and SD (BOTTOM) of peak force in visual and auditory feedback conditions across younger and older adults in the elbow and jaw.
Figure C.8 CV of peak force in visual and auditory feedback conditions across younger and older adults in the elbow and jaw.
Figure C.9 Mean (TOP) and SD (BOTTOM) of time to peak force in visual and auditory feedback conditions across younger and older adults in the elbow and jaw.

Auditory Feedback

Visual Feedback

<table>
<thead>
<tr>
<th></th>
<th>Young</th>
<th>Old</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>SD of Time to Peak Force (ms)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Elbow</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Jaw</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Young</th>
<th>Old</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Mean Time to Peak Force (ms)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Elbow</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Jaw</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Figure C.10 Coefficient of variation of time to peak force in visual and auditory feedback conditions across younger and older adults in the elbow and jaw.
Figure C.11 Mean (TOP) and SD (BOTTOM) of peak rate in visual and auditory feedback conditions across younger and older adults in the elbow and jaw.
Figure C.12 Coefficient of variation of peak rate in visual and auditory feedback conditions across younger and older adults in the elbow and jaw.
Figure C.13 Mean skewness (TOP) and kurtosis (BOTTOM) of the force trajectory in visual and auditory feedback conditions across younger and older adults in the elbow and jaw.
Figure C.14 Integrated force trajectory fit to a logistic of all experimental conditions

Auditory Feedback

Visual Feedback

Template
Y. Elbow
O. Elbow
Y. Jaw
O. Jaw

Time (ms)

Impulse (N*s)
Table C.1. Mean Inflection Point as a function of Age, Feedback, and Effector

<table>
<thead>
<tr>
<th>Feedback</th>
<th>Group</th>
<th>Effector</th>
<th>Younger</th>
<th>Older</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Elbow</td>
<td>165</td>
<td>187</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Jaw</td>
<td>122</td>
<td>177</td>
</tr>
<tr>
<td><strong>Auditory</strong></td>
<td></td>
<td>Elbow</td>
<td>162</td>
<td>204</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Jaw</td>
<td>143</td>
<td>197</td>
</tr>
<tr>
<td><strong>Visual</strong></td>
<td></td>
<td>Elbow</td>
<td>162</td>
<td>204</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Jaw</td>
<td>143</td>
<td>197</td>
</tr>
</tbody>
</table>

*p < .05, **p<.01
Figure C.15 Standard deviation (TOP) & CV (BOTTOM) of the inflection in visual and auditory feedback conditions across younger and older adults in the elbow and jaw.
APPENDIX D: CORRELATIONS BETWEEN FORCE PRODUCTION ACCURACY, VARIABILITY AND SENSORY DISCRIMINATION FROM EXPERIMENT 2
Table D.1 Correlations between Discriminability Tests and Feedback Conditions

Mean AE of Peak Force

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Auditory</td>
<td>0.69**</td>
<td>-0.10</td>
<td>-0.01</td>
<td>-0.12</td>
</tr>
<tr>
<td>Visual</td>
<td>-0.21</td>
<td>-0.23</td>
<td>0.01</td>
<td>0.10</td>
</tr>
</tbody>
</table>

*p < .05, **p<.01; E stands for Elbow, J stands for Jaw

Table D.2 Correlations between Discriminability Tests and Feedback Conditions

Mean AE of Time to Force

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Auditory</td>
<td>-0.20</td>
<td>0.65*</td>
<td>-0.14</td>
<td>0.47*</td>
</tr>
<tr>
<td>Visual</td>
<td>-0.19</td>
<td>-0.25</td>
<td>-0.21</td>
<td>-0.41*</td>
</tr>
</tbody>
</table>

*p < .05, **p<.01; E stands for Elbow, J stands for Jaw
### Table D.3 Correlations between Discriminability Tests and Feedback Conditions

**SD of Time to Peak Force**

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Auditory</td>
<td>-0.30</td>
<td>0.47*</td>
<td>0.21</td>
<td>0.13</td>
</tr>
<tr>
<td>Visual</td>
<td>-0.30</td>
<td>-0.16</td>
<td>0.07</td>
<td>-0.12</td>
</tr>
</tbody>
</table>

*p < .05, **p<.01; E stands for Elbow, J stands for Jaw

### Table D.4 Correlations between Discriminability Tests and Feedback Conditions

**SD of Impulse**

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Auditory</td>
<td>-0.02</td>
<td>0.43*</td>
<td>-0.08</td>
<td>0.08</td>
</tr>
<tr>
<td>Visual</td>
<td>-0.63*</td>
<td>-0.47*</td>
<td>-0.38*</td>
<td>-0.31</td>
</tr>
</tbody>
</table>

*p < .05, **p<.01; E stands for Elbow, J stands for Jaw
### Table D.5 Correlations between Discriminability Tests and Feedback Conditions

**Skewness**

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Auditory</td>
<td>-0.10</td>
<td>-0.38*</td>
<td>-0.10</td>
<td>-0.29</td>
</tr>
<tr>
<td>Visual</td>
<td>0.42*</td>
<td>-0.11</td>
<td>0.36*</td>
<td>-0.20</td>
</tr>
</tbody>
</table>

*p < .05, **p<.01; E stands for Elbow, J stands for Jaw

### Table D.6 Correlations between Discriminability Tests and Feedback Conditions

**Kurtosis**

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Auditory</td>
<td>0.08</td>
<td>0.62**</td>
<td>-0.15</td>
<td>0.45*</td>
</tr>
<tr>
<td>Visual</td>
<td>-0.29</td>
<td>0.02</td>
<td>-0.15</td>
<td>-0.20</td>
</tr>
</tbody>
</table>

*p < .05, **p<.01; E stands for Elbow, J stands for Jaw