5-8-2015

Variability in bimanual coordination across the continuum of handedness.

Kaitlin Oswald

Recommended Citation

Oswald, Kaitlin, "Variability in bimanual coordination across the continuum of handedness." (2015). *Master's Theses and Doctoral Dissertations*. 634.
http://commons.emich.edu/theses/634

Variability in Bimanual Coordination across the Continuum of Handedness

by

Kaitlin A. Oswald

Thesis

Submitted to the Department of Psychology

Eastern Michigan University

in partial fulfillment of the requirements

for the degree of

MASTER OF SCIENCE

In

Clinical Psychology

Thesis Committee:

Jin Bo, Ph.D., Chair

Catherine Peterson, Ph.D.

Norm Gordon, Ph.D.

Kenneth Rusiniak, Ph.D.

Date: May 8, 2015

Ypsilanti, MI

Abstract

Bimanual coordination is an essential human function requiring efficient interhemispheric communication to produce coordinated movements. Motor deficits affect a variety of clinical populations, yet a complete understanding of bimanual coordination has yet to be achieved. Previous research suggests performance variability depends on the phase demands of the coordinated task and completing bimanual tasks may result in less variability than unimanual tasks, or a bimanual advantage. Also, handedness and musical/athletic experience have also been shown to influence coordinated performance. The present study examined the existence of a bimanual advantage and potential factors influencing coordination in a tapping paradigm. Results indicated that the strong-handed individuals displayed a strong bimanual advantage; whereas, weak-handed participants had a weak bimanual advantage. Variability did not differ by musical/athletic experience. In light of the present findings, relevant studies are needed to gain further insight into bimanual coordination and the underlying processes of motor movement.

Table of Contents

List of Tables

Table Page

Definitions

1. Anti-phase: Synchronized movement of non-homologous muscles moving 180o out-of-phase. For example, the right finger and left finger would tap with identical frequencies; however, the phase difference between fingers would be exactly 180^o.
2. Bimanual Movements: Coordinated inter-limb movements between two hands or limbs.
3. In-phase: Simultaneous movement of homologous muscles. For example, the right and left fingers would tap in synchrony to execute an in-phase pattern.
4. Out-of-phase: Asynchronous movements with muscular phase differences ranging from 0o to 360o. Anti-phase tapping is a form of out-of-phase tapping. For example, a lag period between the right finger and left finger tapping produces an out-of-phase pattern.
5. Unimanual Movements: Coordinated movement of one hand or limb.

Introduction

Every day, humans unconsciously execute coordinated movements between hands; however, these ubiquitous tasks require precise coordination patterns with both temporal and spatial precision. For instance, putting on a coat appears effortless, but requires each hand to function independently yet coordinate together. Deficits in the interhemispheric communication required to execute these tasks can result in impairments in motor dexterity and may manifest as a symptom of a variety of neurological and psychological disorders (Volman, Laroy, & Jongmans, 2006). Gaining insight into bimanual coordination may lead to future clinical benefits.

It is evident that communication across hemispheres is imperative for the execution of motor movements; however, the crosstalk between hemispheres may vary depending on synchrony and involvement of both hands. For instance, research has revealed that tasks requiring in-phase movements of both hands resulted in less variability compared to unimanual tasks, or movements incorporating the use of only one hand, suggesting the presence of a bimanual advantage (Ivry & Hazeltine, 1995; Helmuth & Ivry, 1996). One potential explanation for this observed difference is the increased neural activity, specifically inhibition, which may occur across the corpus callosum during unimanual tasks (Duque et al., 2005). Further research is still necessary to further exemplify and understand the existence of a bimanual advantage.

In addition, research findings suggest hand dominance may affect the consistency of the patterns of temporal variability previously observed in bimanual and unimanual tasks. For instance, it has been found that the strength of handedness, weak versus strong, may influence motor performance on in-phase and out-of-phase tasks (Kourtis, Sadler, & Vingerhoets, 2014). Additionally, brain-imaging research has shown that individuals with strong and weak lateralization have structural and functional differences in specific brain regions, such as the corpus callosum (Fling et al., 2011b; Kourtis et al., 2014; Witelson, 1985 & 1989). Overall, further investigation of the effects of handedness is still necessary to fully understand the function strong or weak lateralization may have on bimanual motor coordination.

Furthermore, it has been found that previous musical and athletic experience may relate to differences in neural activity. For instance, the degree of neural activity has been shown to be less in individuals with extensive experience playing an instrument (Jancke, Shah, & Peters, 2000). Also, region specific activation may also differ between expert athletes and musicians compared to non-musicians or non–athletes (Kim et al., 2008; Munte, Nager, Beiss, Schroeder, & Altenmuller, 2003). Evidently, there are neurological differences, such as degree of activity, between experienced athletes and musicians compared to those with no experience (Jancke et al., 2000; Munte et al., 2003). Therefore, musical and athletic experience should be taken into consideration and further investigated when assessing motor coordination as neurological variations may affect coordinated activities, which is dependent upon neurological communication.

An extensive body of research has analyzed variability in completing coordination tasks; however, the empirical findings on the relationship between handedness and temporal variance in coordination in a tapping paradigm are limited. The purpose of this study is to elucidate the consistency of variability across unimanual and bimanual movements utilizing a finger tapping paradigm and to investigate temporal variance in several coordination patterns by degree of hand dominance. Also, this study aims to assess the relationship between previous musical and athletic experience on bimanual motor coordination efficiency. The following sections review the existing body of literature on the behavioral and neuroanatomical findings of coordination and hand dominance and the manifestation of coordination developmentally and in clinical populations. Additionally, the relationship between previous musical and athletic experience with bimanual coordination is also discussed. To conclude, a rationale of the aims and proposed hypotheses of this study are provided.

Literature Review

Clinical Relevance

Impairments in motor dexterity have been observed in many neurological disorders, such as Parkinson's Disease (Brown, Jahanshahi, & Marsden, 1993), Huntington's Disease (Johnson et al., 2000), and cerebellar disease (Serrien & Wisendanger, 2000). Motor deficits are also a primary symptom of a wide range of neurodevelopmental disorders, such as Developmental Coordination Disorder (DCD) and Autism Spectrum Disorder (ASD) (APA, 2013). It has been reported that children with DCD often experience impaired motor coordination development and have disordered handwriting (Kirby & Sugden, 2007). Specifically in coordinated tasks, children with DCD tend to perform slower on a variety of coordinated tasks (e.g., one hand versus two hands and continuous versus discontinuous) compared to children with normal motor development (Bo, Bastian, Kagerer, Contreras-Vidal, & Clark, 2008; Huh, Williams, & Burke, 1998; Volman, Laroy, & Jongmans, 2006). Individuals with ASD also experience motor coordination deficits according to a meta-analysis of 83 ASD studies (Fournier, Hass, Naik, Lodha, & Cauraugh, 2010). Specifically, children with ASD have been shown to perform significantly more variably on both synchronized and asynchronized, or more complex, coordination tasks compared to typically developing children (Isenhower et al., 2012). These disorders are a few examples of the wide range of motor deficits observed in clinical populations and exemplify the importance of continuing to research motor movement.

Moreover, gaining more in-depth knowledge of motor coordination can lead to a better understanding of psychological diseases that are less commonly associated with motor impairments, such as psychotic disorders. For instance, empirical evidence suggests schizophrenic patients display reduced motor asymmetries when completing two handed tasks compared to healthy control participants (Tabares-Seisdos et al., 2003). Also, children and adolescents presenting with psychosis have displayed decreased stability performing a finger tapping task with their dominant hand compared to healthy subjects and individuals with other psychological disorders (Gorynia, Dudeck, & Neumarker, 1994). More specifically, Gorynia and Schwaiger (2011) found that impairments in coordination can vary even by the duration of the psychotic disorder and by the presence or absence of negative symptoms. As suggested by Gorynia, Campman, and Uebelhack (2003) gaining insights into motor coordination and the underlying neurological processes of coordination in psychotic disorders may lead to advancements in prognosis of psychotic disorders. Overall, a wide range of neurological and psychological disorders result in motor impairments and may benefit from research focusing on the understanding and analysis of coordination.

Behavioral Findings in Coordination

Synchrony. Coordinated inter-limb bimanual, or two-handed, movements can manifest in various relative phase patterns. For instance, bimanual movements can be executed with homologous muscles moving in-phase (Swinnen, Jardin, Meulenbroek, Dounskaia, & Hofkens-Van Den Brandt, 1997; Swinnen, 2002). In a tapping paradigm, both the right and left index fingers tap simultaneously to maintain an in-phase pattern. Additionally, synchronized bimanual movements can also be produced by nonhomologous muscles moving 180^{o} out-of-phase at equal frequencies, which is referred to as anti-phase (Kelso, 1984; Swinnen, 2002; Swinnen et al., 1997). Moreover, a synchronized, anti-phase pattern can be maintained even if the muscles function in opposite directions. For example, in order to maintain anti-phase patterns in a tapping paradigm, the right and left index fingers must tap at identical frequencies with a 180^{o} phase difference. Furthermore, asynchronous bimanual movements can also be produced with interlimb muscular out-of-phase differences ranging from 0^{o} to 360^{o} (Kelso, 1984; Semjen & Ivry, 2001). In a tapping paradigm, an out-of-phase bimanual pattern can be produced by incorporating a lag period between the right and left finger tapping. These phase delays in bimanual movements often result in more temporal variability and instability in hand coordination (Semjen & Ivry, 2001; Swinnen, 2002).

Specifically in a tapping paradigm, evidence suggests in-phase synchrony to be more accurate compared to anti-phase bimanual movements. Work by Serrien (2008) revealed bimanual in-phase movements of a two finger combination, index and middle, produced more accurate coordination compared to bimanual out-of-phase movements. Additionally, recent findings suggested that between hand variability for in-phase repetitive finger tapping was lower than variability in asynchronous, out-of-phase finger tapping (Bangert, Reuter-Lorenz, Walsh, Schachter, & Seidler, 2010). In both studies, in-phase coordinated bimanual tapping proved to be more accurate and stable compared to out-of-phase tapping at various phase delays.

In addition, in-phase movements have also proven to be the preferred phase of bimanual movements. Human bimanual cyclic movements have displayed a tendency to shift from anti-phase coordination towards in-phase coordination as movement frequencies increase (Kelso, 1984; Swinnen, 2002). This preference towards in-phase bimanual movements may be a product of the desire to produce more energetically efficient movements (Kelso, 1984). In Repp's (2005) extensive review of the literature on sensiomotor synchronization and tapping, he comments that rhythmic motor movement in response to external stimuli may be particular to humans due to the lack of evidence exemplifying this phenomenon in other animals. These behavioral findings in temporal variability and phase transitions suggest that synchronized in-phase bimanual movements have proven to be advantageous compared to out-of-phase or anti-phase bimanual actions.

Bimanual Advantage. Further research also suggests that bimanual movements may be more efficient compared to unimanual, or one-handed, movements. In a tapping paradigm, tapping with two fingers, one from the right hand and one from the left hand, resulted in reduced temporal variance compared to unimanual tapping (Bangert et al., 2010; Drewing & Aschersleben, 2003; Drewing, Hennings, & Aschersleben, 2002; Helmuth & Ivry, 1996; Studenka, Eliasz, Shore, & Balasubramanian, 2014). This phenomenon has been referred to as a “bimanual advantage” and was originally studied by Helmuth and Ivry (1996) by assessing tapping variability under various coordination conditions and limb combinations. They found within hand temporal variability in a repetitive tapping task was consistently reduced when tapping in a bimanual in-phase pattern with both the right and left index fingers compared to unimanual tapping (Helmuth & Ivry, 1996). Similarly, this bimanual advantage was observed when participants completed the task with nonhomologous muscles (Helmuth & Ivry, 1996). Moreover, making coordinated movements with the index finger of one hand combined with the fist of another hand resulted in better performance compared to performance of either the index finger or fist independently (Helmuth & Ivry, 1996).

Since the work conducted by Helmuth and Ivry (1996), researchers have published controversial findings evident for and against a bimanual advantage. Research on the role of sensory information in bimanual coordination has supported the bimanual advantage in a simple tapping paradigm (Drewing & Aschersleben, 2003; Drewing et al., 2002; Studenka et al., 2014). For instance, Drewing et al. (2002) predicted that increased sensory information would improve timing. In this study, participants completed two experimental conditions: tapping with the right hand index finger only and tapping the right hand index and middle fingers in synchrony (Drewing et al., 2002). Results from this study suggest tapping was more consistent tapping when the index finger was coupled with the middle finger compared to the index finger tapping independently (Drewing et al., 2002). Despite investigating bidigital coordination compared to multi-limb bimanual movements, these results still support the concept of a bimanual advantage. Additionally, Bangert et al. (2010) found that the bimanual advantage is also reproducible in older adults despite potential global deficits in motor coordination, which suggests that this advantage may even occur across the lifespan.

On the contrary, Serrien's (2008) findings did not support the bimanual advantage. In this study, using a two-finger combination of the index and middle fingers, participants completed a variety of coordinated experimental conditions: unimanual in-phase, unimanual anti-phase, bimanual in-phase, and bimanual anti-phase (Serrien, 2008). Results supported a significant main effect by task, unimanual versus bimanual, in that participants had more coordinative accuracy on unimanual conditions compared to the bimanual conditions (Serrien, 2008). Unlike the Drewing et al. (2002) study, Serrien's study did not exemplify the presence of a bimanual advantage in coordinated tasks. One potential explanation for such discrepancy may be due to the different measures used in these studies. Serrien (2008) focused on accuracy measures while the other studies primarily focused on the temporal consistency. It was not clear as to whether there was a speed/accuracy trade-off in that study (Serrien, 2008). Although the empirical evaluation of the bimanual advantage is limited and may suggest variability in the theory of bimanual advantage, several researchers have been able to support the idea that temporal variability improves during synchronized bimanual tapping compared to unimanual tapping

(Bangert et al., 2010; Drewing & Aschersleben, 2003; Drewing et al., 2002; Helmuth & Ivry, 1996).

In addition, several researchers have attempted to formulate theories to explain the bimanual advantage observed in repetitive tapping tasks. A prominently used and well supported model of timing and repetitive motor movements was developed by Wing and Kristofferson (1973a, 1973b). This model assumes an internal timer, or timekeeper, controls tapping intervals with a motor delay before initiating the motor command, or tap (Drewing & Aschersleben, 2003). Researchers have attempted to apply the Wing and Kristofferson model to both single limb and multi-limb coordination tasks. According to the Wing and Kristofferson model, one time keeper would trigger motor commands simultaneously in both limbs during bimanual coordination tasks resulting in temporal variability similar to unimanual coordination (Drewing & Aschersleben, 2003). However, as previously discussed, Helmuth and Ivry (1996) did observe improved temporal variance in bimanual tasks.

As a result, Helmuth and Ivry (1996) suggested modifications to the Wing and Kristofferson (1973a) model that would explain their findings of a bimanual advantage. According to Helmuth and Ivry (1996), each effector, or hand, has an individual timer, and the outputs for each effector are averaged before the motor commands were triggered. This integration of effector-specific timers resulted in decreased variability of bimanual movements compared to unimanual movements due to the average of two timer signals being smaller compared to that of an individual timer (Drewing & Aschersleben, 2003; Studenka et al., 2014). From the perspective of Helmuth and Ivry (1996), a cognitive theory has been postulated to explain bimanual advantages; however, researchers have also formulated a sensory or enhanced feedback theory to explain this phenomenon.

The alternative hypothesis postulates that sensory input from each effector contributes to the reduced timing observed in bimanual tasks. This hypothesis is supported by empirical findings exemplifying that sensory input to one finger during bimanual tasks can influence the temporal variability observed in the alternate finger (Drewing & Aschersleben, 2003; Drewing et al., 2002). For instance, when sensory feedback was reduced in participants' left finger overall temporal variance increased in a bimanual task compared to when both fingers received sensory input by touching the table (Drewing et al., 2002). In addition to tactile feedback, auditory feedback has proven to increase variability in a bimanual task. For example, when auditory input was only provided for right handed tapping the bimanual advantage was reduced compared to when auditory feedback was provided for both left and right handed tapping (Drewing & Aschersleben, 2003). In relation to the model proposed by Wing and Kristoferson (1973a,1973b), Drewing & Aschersleben (2003) propose that sensory reafferences may strengthen the bimanual advantage by detecting and correcting errors and by predicting future movements.

Overall, empirical findings have supported the existence of a bimanual advantage in coordinated tapping tasks. The cognitive, multiple effector model and the sensory, enhanced the feedback model's attempt to better explain the bimanual advantage observed in bimanual tapping tasks; however, a conclusive explanation has yet to be discovered. It is also possible that other factors influence motor timing variability. Within the present study, laterality of handedness is further investigated as a potential moderator of temporal variability in bimanual coordination.

Handedness

In the study of motor coordination, many researchers have been interested in further understanding the relationship between hand dominance and various functions, such as motor coordination. Generally, handedness is assumed to be a dichotomous variable with two directions, right or left. However, some researchers have empirically conceptualized handedness as a continuous variable (Annett, 1976; Corey, Hurley, & Foundas, 2001; Fagard & Durding, 1978). According to Annett's (1976) early findings, hand dominance can be categorized as a continuous variable from both a performance and preference perspective. In her study, she found that participants could be categorized by continuously distributed variables of preference as reported by each participant and by each participant's performance on a peg moving task (Annett, 1976). Annett concluded from her findings that future research on manual coordination and laterality should focus on subgroups across the distribution of handedness instead of focusing primarily on left/right handedness.

Similar findings have also been replicated utilizing a finger tapping task. Peters and Durding (1978) found that left and right hand differences on a repetitive finger tapping task were linearly related to preference as reported by Oldefield's (1971) laterality quotients. These results provide further support for Annett's (1976) concept of handedness being a continuous variable. Additionally, Peters and Durdling (1978) concluded that performance or preference based assessments of handedness do not adequately assess for hand dominance alone. Recent findings further support this idea and suggest that multiple forms of assessing handedness can distinguish distinct handedness subgroups (Corey et al., 2001). All together, these results suggest that hand dominance can indeed be formulated as a continuous variable, especially if multiple forms of assessing handedness are included.

Furthermore, perceiving handedness as a continuous variable can enhance the empirical findings on motor coordination. For instance, Gorynia and Egenter found that left handed participants with low laterality quotients had significantly higher intermanual coordination and smaller asymmetry in a finger tapping task (2000). In other words, individuals who indicated that they were less strongly left-handed could complete tapping tasks using both hands faster and with greater efficiency compared to left handed participants with high laterality quotients and right handed participants. Additionally, ambidextrous participants have been shown to perform more rapidly on a unimanual box task with both hands compared to strongly handed individuals, which resulted in a U shaped distribution of hand preference as a continuum and manual performance (Ponton, 1987). On the other hand, these results have not been replicated in children. In Fagard and Corroyer's (2002) study, laterality as a continuous index was not found to be significantly correlated with several bimanual tasks, including simultaneous and alternating finger tapping. Several factors may have contributed to these opposing results, such as comparative development of neuronal structures in children and adults and the limited breadth of research on the relationship between laterality and motor coordination.

In a more recent study, the relationship between motor coordination and laterality was analyzed including both right- and left-handed individuals with consistent and inconsistent handedness (Kourtis, Saedeleer, & Vingerhoets, 2014). In this study, participants with consistent hand dominance performed slower on an asymmetrical task compared to a symmetrical visuospatial tapping task (Kourtis et al., 2014). In other words, participants who reported strong left or right hand dominance had slower response times on the more complex, asymmetric task. However, participants with inconsistent hand dominance performed equally fast on both symmetrical and asymmetrical motor tasks (Kourtis et al., 2014). Even though the results varied within each group, Kourtis et al. (2014) found that participants with inconsistent hand dominance were equally accurate in performing asymmetrical and symmetrical movements as those with consistent hand dominance. These results suggest that the degree of handedness may have an influence on the initiation and planning of bimanual movements; however, further investigation is needed to assess the influence of hand dominance on bimanual movements.

In light of these findings, further investigation of the effects of handedness is still necessary. Many studies continue to consider handedness as primarily a dichotomous variable or completely exclude left-handed individuals from data collection and analysis. Additionally, researchers have yet to investigate the relationship between handedness as a continuous variable and the bimanual advantage previously observed in coordinated motor movements. Evidently, researchers are beginning to consider handedness as a continuous variable; however, this conceptualization of hand dominance is still innovative and under studied.

Functional Neuroscience of Coordination

Even though the objective of this study is to seek behavioral evidence of a bimanual advantage and potential advantages in motor coordination according to hand dominance, it is also important to consider the neurological underpinnings of these advantages. In the bimanual coordination literature, researchers have identified multiple brain regions that are involved with the execution of motor tasks, such as the primary and supplementary motor areas, premotor area, cerebellum, cingulate motor cortex, premotor cortex, and corpus callosum (Debaere, Wenderoth, Van Hecke, & Swinen, 2004; Swinnen & Wenderoth, 2004). Also, research findings have found correlations between specific anatomical regions in the brain and specific motor coordination conditions, which are further discussed below. Understanding these correlations can lead to a better understanding of the predicted behavioral bimanual advantage.

As previously mentioned, behavioral findings have illustrated that out-of-phase bimanual tasks result in greater variability compared to in-phase bimanual tasks (Serrien, 2008). According to neurological evidence in a positron emission tomography (PET) study, the increased variability observed during out-of-phase bimanual tasks may be a result of increased neural activations in brain regions involved in spatial and temporal execution of motor tasks, such as the supplementary motor area and dorsal premotor area (Sadato, Yonekura, Waki, Yamada, & Ishii, 1997). Also, findings from a functional magnetic resonance imaging (fMRI) study indicated that the bilateral superior temporal gyri, in addition to the pre-supplementary motor area, may be pertinent for the execution of out-of-phase bimanual movements (Ullen, Forssberg, & Ehrsson, 2002). Evidently, the increased brain activity observed in asynchronous tasks is functionally pertinent to control the precise and independent movements of both hands.

Neuroimaging of participants completing out-of-phase coordinated motor movements have also displayed an up-regulation of intracortical inhibition compared to synchronized motor movements (Stinear & Byblow, 2002). Moreover, intracortical inhibition was suppressed when completing in-phase bimanual movements compared to out-of-phase bimanual movements. This may be a product of the increased demand on controlling two independent muscles and movements at opposite phases. Additionally, participants in an EEG study displayed more interhemispheric coupling when executing anti-phase conditions compared to in-phase conditions (Serrien, 2008). These results, again, exemplify the importance of increased information processing in asynchronous tasks compared to synchronized tasks.

Similarly, unimanual motor tasks require interhemispheric inhibition to suppress the movement of the contralateral limb (Duque et al., 2005; Fagard & Hardy-Leger, 2001; Geffen, Jones, & Geffen, 1994; Meyer, Roricht, Einsiedel, Kruggel, & Weindl, 1995; Sohn, Jung, Kaelin-Lang, & Hallett, 2003; Tinazzi & Zanette, 1998; Vercauteren, Pleysier, Van Belle, Swinnen, & Wenderoth, 2008). The corpus callosum functions as a primary center for inhibition and facilitation between motor cortices and plays a critical role in motor movements

(Vercauteren et al., 2008; Fling, Benson, & Seidler, 2013). During unimanual tasks, interhemispheric inhibition occurs across the corpus callosum to counteract the contralateral limb from producing default mirror movements of the active hand (Duque et al., 2005). In a sample of children, a lack of interhemispheric inhibition resulted in increased mirror movements during the execution of a unimanual task (Fagard & Hardy-Leger, 2001). As children's brains develop and interhemispheric communications improve, bimanual efficiency will also increase. Evidently, interhemispheric inhibition proves to be an important and necessary component of executing both asynchronous bimanual and unimanual tasks.

On the other hand, synchronized bimanual coordination has displayed an alternate pattern of brain activation. For instance, participants have exhibited more bilateral and lower activation across the parietal cortex according to functional magnetic resonance imaging of a bimanual task compared to a stronger neural response during a unimanual condition (Heitger, Mace, Jastorff, Swinnen, & Orban, 2012). In other words, the bimanual conditions appeared to exhibit more shared activation patterns with less intensity compared to the unimanual conditions, which had stronger activation and more left or right hemisphere dominance. Additionally, Chen et al. (2005) revealed through transcranial magnetic stimulation that neither the right nor left hemisphere is dominant during in-phase bimanual movements. Similar results were also found in an fMRI study that required participants to complete a two-finger bimanual task by navigating a cursor on a computer screen (Koeneke, Lutz, Wustenberg,& Jancke, 2004). The authors concluded that bimanual coordination is both less behaviorally demanding and requires less neural activation compared to unimanual coordination (Koeneke et al., 2004).

In addition to differences in functional activity, disparate interhemispheric connectivity patterns have also been observed during in-phase bimanual tasks compared to unimanual tasks

(Serrien, 2008). These results suggest that more interhemispheric communication is required during unimanual movements, which may explain the bimanual advantage observed in coordinated tasks. In contrast to interhemispheric connectivity, several researchers have hypothesized an alternate neural foundation for synchronized bimanual coordination (Pollok, Butz, Gross, & Schnitzler, 2007). This conclusion was made based on observed elevated intercerebellar coupling, or communication between the two hemispheres of the cerebellum, during the execution of an in-phase bimanual task compared to both bimanual asynchronous and unimanual tasks (Pollok et al., 2007). Furthermore, callosotomy patients have displayed the bimanual advantage, which suggests that the corpus callosum may not be responsible for synchronized bimanual movements (Ivry & Hazeltine, 1999). Reportedly, callosotomy patients have displayed intact temporal synchrony when executing motor movements despite having spatial variability (Franz, Eliassen, Ivry, & Gazzaniga, 1996; Gerloff & Andre, 2002). Taken all together, the exact role of the corpus callosum in bimanual coordination is still uncertain; however, the increased interhemispheric inhibition observed during unimanual tasks is a possible explanation for the bimanual advantage.

Neurological findings can also explain predicted and observed motor performances dependent upon hand dominance. In a study assessing strongly right-handed children, stronger left hemisphere motor connectivity was positively correlated with higher performance on the physical and neurological examination for soft signs (PANESS), which is a battery of motor control (Barber et al., 2012). In other words, individuals with greater connectivity in the left hemisphere compared to the right, or left hemisphere dominance, performed better on motor tasks. This study has several limitations, such as sampling only right-handed participants and using a broad motor assessment. However, the increased performance in strongly handed, or left lateralized, participants can support the prediction that strongly handed participants will potentially perform better on motor tasks compared to participants with less hand dominance.

Moreover, callosal differences have also been observed in those with strong and weak hand dominance. Empirical evidence from a study measuring the post mortem callosal size of individuals previously given neuropsychological assessments has shown that individuals with less hand dominance have larger corpus callosums (Witelson, 1985 & 1989). Also, data from magnetic resonance imaging (MRI) studies have also shown that individuals with less consistent hand dominance have larger corpus callosums (Habib et al., 1991; Luders et al., 2010). These results suggest that callosal size may be more closely related to the degree of handedness rather than the direction of handedness. Additionally, individuals with larger corpus callosums have displayed poor performance on out-of-phase bimanual tasks according to an MRI study (Fling et al., 2011b). The authors suggest that this relationship may be a result of excessive interhemispheric inhibition and improper activation of the motor cortex, which decreases temporal performance on out-of-phase tasks (Flint et al., 2011). All together, these results can lead to the prediction that individuals with weak hand dominance may have poor performance on out-of-phase motor tasks.

As previously mentioned, empirical evidence has suggested that less interhemispheric connectivity is required to execute synchronized bimanual tasks (Pollok et al., 2007; Serrien, 2008). Therefore, it can also be predicted that individuals with weak hand dominance will perform better on in-phase bimanual tasks and yield greater evidence of a bimanual advantage. To further support this prediction, recent findings have suggested that individuals with inconsistent hand preference, or weak hand dominance, have larger Movement Related Potentials (MRP) (Kourtis, Saedeleer, & Vingerhoets, 2014). An MRP is a readiness potential that measures neural activation in the motor cortex and supplementary motor area leading up to a motor movement (Kourtis, Saedeleer, & Vingerhoets, 2014). This relationship suggests that individuals with decreased hand dominance may have an advantage in the planning of bimanual movements, which further supports the prediction of individuals with weak hand dominance yielding greater performance on synchronized bimanual tasks.

Developmental Neuroscience

In addition to understanding the functional connectivity involved in motor movements, the development of these processes should also be taken into consideration. As previously mentioned, the corpus callosum can play a major role in the successful execution of motor movements; however, structural differences in the corpus callosum have yielded varying effects in younger and older adults (Fling et al., 2011a, 2011b). In an fMRI study, researchers assessed the effects of callosal size on cognitive functions through a broad battery of cognitive tests, including a reading span task, digit span tasks, and a digit-symbol substitution test (Fling et al., 2011a). The results of this study indicated that the size of the corpus callosum had no relationship with cognitive abilities in younger adults, ages 18 to 30 (Fling et al., 2011a). On the other hand, older adults, ranging from 65 to 80 years old, demonstrated a positive relationship between callosal size and cognitive performance (Fling et al., 2011a). Within the group of older adults, individuals with larger corpus callosums perform better cognitively; however, their performances on cognitive tasks were still lower than younger adults with similarly sized corpus callosums.

Specifically in a tapping paradigm, inconsistencies in performance and callosal sizes have been demonstrated in younger and older adults. Fling et al. (2011b) found opposing relationships between the size of the corpus callosum and performance on unimanual and out-of-phase bimanual tapping tasks with younger adults demonstrating a negative relationship and older adults displaying a positive relationship. In other words, a larger corpus callosum appeared to be beneficial for older adults but related to decreased performance in younger adults. No significant relationships were found between callosal size and performance during the synchronized bimanual condition for both younger and older adults. The authors hypothesize that the relationship observed in younger adults may be a result of overflow and excessive inhibition across the corpus callosum, which may decrease efficiency when executing out-of-phase and unimanual tasks that require precise interhemispheric inhibition (Fling et al., 2011b). Furthermore, the authors suggest that the potential overflow experienced in young adults with large corpus callosums may not occur in older adults with larger corpus callosum (Fling et al., 2011b). This hypothesis may explain the improved performance observed in older adults with larger corpus callosums. Overall, it is evident that the corpus callosum structure and function may vary throughout human development.

Handedness has also proven to have varying relationships with functional activity in younger and older adults. In young adults, handedness has been shown to be negatively correlated with ipsilateral brain activation in a transcranial magnetic stimulation study (Bernard, Taylor, & Seidler, 2011). On the other hand, lateralization of dexterity in older adults has been shown to be positively correlated with both ipsilateral and contralateral brain activity (Bernard et al., 2011). This is yet another example of the potential functional differences of the corpus callosum across the life span. Further investigation of the structure-function evolution of the corpus callosum throughout human development is still necessary; however, these potential developmental alterations must be taken into consideration when studying movement and handedness.

In early development, empirical findings suggest the corpus callosum is also undergoing significant structural changes. Research shows that callosal size increases throughout childhood into adolescence with the greatest increases occurring in early childhood (Gbedd et al., 1999; Paus et al., 1999). Reportedly, complete maturation of the human corpus callosum is not achieved until an individual is in their twenties (Pujol, Vendrell, Junque, Marti-Vilalta, & Capdevila, 1993). But unfortunately, there is a lack of studies on bimanual coordination in early development. Further assessment of the neurodevelopment in childhood is still necessary. Taken all together, evidence of callosal maturation into late adolescence and developmental changes in late adulthood, young to mid-life adults may be an optimal population to examine motor coordination.

Musical and Athletic Experience

In the assessment of motor efficiency, it is important to take into consideration various factors that may influence brain activity, which as a result, influence motor abilities. A potential influential variable in motor coordination is the level of experience participants have in music or sports because experience in these areas have displayed differences in neural activity (Jancke, Shah, & Peters, 2000; Hatfield Haufler, Hung, & Spalding, 2004; Ross, Tkach, Ruggieri, Lieber, & Lapresto, 2003). For instance, in an fMRI study assessing cortical activation in professional pianists, less brain activity was observed in the primary and secondary motor areas in musicians compared to non-musicians (Jancke et al., 2000). Similarly, fMRI and EEG studies have found that expert athletes have less cortical activation, specifically in the supplementary motor area and cerebellum, than to novice athletes (Hatfield et al., 2004; Ross et al., 2003). Also, decreased muscle activation has been observed in individuals who practice motor tasks (Lay, Sparrow, Hughes, & O’Dwyer, 2002). However, empirical findings also suggest that the reduced neurological activity observed by an EEG may only occur when experts, e.g., marksmen and shooters, are completing motor tasks that they have practiced extensively, and the decreased activation may not occur when experts complete novel motor tasks (Haufler, Spalding, Santa Maria, & Hatfield, 2000). Nonetheless, musicians and athletes have displayed decreased brain activity when completing motor tasks. As suggested by Milton, Solodkin, Hlustik,and Small (2007), experts may have a refined and efficient neural organization, while novices have less neural filtering and efficiency. Therefore, expert athletes and musicians may not need as much neural activity to execute motor tasks.

Furthermore, brain imaging research has shown that different brain regions are activated when experts complete motor tasks compared to novices. For example, event-related brain potential studies have found that musicians have different neural correlates for processing auditory cues compared to non-musicians (Munte, Altenmuller, & Jancke, 2002; Munte, Nager, Beiss, Schroeder, & Altenmuller 2003). More specifically, the authors concluded that these differences may be even more specific to the training of the musician, such as conductor versus pianist (Munte, Nager, Beiss, Schroeder, & Altenmuller, 2003). Differences in region-specific neural activation have also been observed in athletes. In an fMRI study, when expert archers aimed, they displayed more activation at the occipital gyrus and temporal gyrus than novice archers; however, novices had more activation in the frontal area than experts when aiming (Kim et al., 2008). Evidently, athletes and musicians have regional differences in brain activity in addition to the level of activity.

In addition to differences in regional cortical activity, researchers have also observed differences in callosal size in musicians compared to non-musicians. For instance, an MRI study revealed that the anterior half of the corpus callosum was significantly larger in male musicians than male non-musicians; however, female musicians did not display any significant differences than female non-musicians (Lee, Chen, & Schlaug, 2003). As well, fMRI studies have revealed that individuals that began performing musically at a young age had significantly larger corpus callosum than musicians that began playing later in life and non-musicians (Schlaug, 2001; Schlaug, Jancke, Huang, Staiger, & Steinmetz, 1995). Furthermore, a diffusion tensor imaging study found that extensive piano practicing can result in an increase in white matter plasticity, specifically when training occurred during childhood, a period when the most myelination occurs (Bengtsson, Nagy, Skare, Forsman, Forssberg, & Ullen, 2005). Altogether, this data further exacerbates the critical involvement of specific brain regions, such as the primary motor area and corpus callosum, in coordinating bimanual movements. Furthermore, individuals with musical and athletic experience appear to have neurological differences compared to those with no experience. A more in depth understanding of these differences and their function may lead to a broader understanding of the musically/athletically experienced brain and bimanual coordination.

Assessing Handedness

Many researchers and clinicians incorporate a measure of handedness into data collection and evaluations. The most commonly used measure of handedness is the Edinburgh Handedness Inventory (EHI) (Oldfield, 1971). The EHI is a brief 10-item self-report questionnaire that prompts individuals to indicate whether or not they complete an everyday task with their right or left hand and the strength of that preference with one check indicating average preference and two checks indicating strong preference. Scoring of the EHI provides a laterality quotient (LQ) that ranges from -1 to +1 (Oldfield, 1971). The EHI was developed primarily as a screener for handedness. In fact, Oldfield reported in his 1971 manuscript that he did not intend for his measurement of handedness to be used in research assessing clinical populations and that his inventory was not the most ideal measurement (Oldfield, 1971). Yet in psychological research, the EHI is commonly used as a primary assessment of handedness for a variety of research questions and clinical populations.

Since the development of the EHI, several researchers have also attempted to create alternative and more efficient measures of handedness. For instance, Marian Annett (1970) attempted to create a handedness measure that efficiently conceptualized handedness as a continuous variable rather than dichotomizing handedness as either right-handed or left-handed. The Annett handedness measure consists of 12 questions assessing whether an individual uses their right, left, or either hand for completing everyday tasks, such as cutting with scissors (Annett, 1970). The items are divided into primary and secondary questions, which Annett formulated from an association analysis. Also, participants can be grouped as either consistent or inconsistent right-handers or left-handers or left or right ambidexters (Annett, 1970). Even though the Annett handedness inventory categorizes participants into different groups, the groupings are still considered to be a part of a larger continuum of handedness.

In general, the Edinburgh Handedness Measure and the Annett Hand Preference Questionnaire have many similarities, such as containing six of the same items. Additionally, both measures have relatively high retest reliabilities. The Annett Hand Preference Questionnaire has a reported kappa coefficient of agreement score equal to +0.80 (McMeekan & Lishman, 1975). In this study, a kappa coefficient was utilized to determine retest reliability since the participants were classified instead of given a numerical score. Also, this study indicated that a sample of participants that was tested twice using the EHI (with fourteen weeks between each testing period) had a product moment correlation coefficient equal to +0.97; however, when the laterality quotient scores were divided into positive and negative values the retest reliability coefficient was +0.75 and +0.86 respectively (McMeekan & Lishman, 1975). In addition, the EHI and Annett questionnaire have reported relatively high internal consistency, coefficient alpha scores of 0.93 and 0.87 respectively (Williams, 1991). According to retest reliability and internal consistency scores, neither measurement appears to be superior to the other.

One major difference, and potential disadvantage of each questionnaire, is the format for scoring the handedness inventories. For instance, the Annett Hand Preference Questionnaire groups individuals into specific groups based on their responses, which fails to indicate where each participant falls on the continuum of handedness (McMeekan & Lishman, 1975). Also, the EHI has some methodological drawbacks in scoring. For instance, the validity of the one-tick versus two tick instructions for the participant is questionable (McMeekan & Lishman, 1975). This system of scoring results in little distinction between degrees of right or left-handedness. Furthermore, the questions on the EHI are not weighted as they are on the Annett Hand Preference Questionnaire; therefore, two ticks versus one tick may have varying degrees of impact on the final LQ based on the weight of that item. It appears that both measures have equal superiority, and yet each measure has flaws in the procedure and scoring.

Since the development of these two measures, Briggs and Nebes (1975) attempted to improve the quality of the Annett Hand Preference Questionnaire and developed a modified version. This altered form has an adjusted scoring procedure, which includes a 5-point scale for participants to indicate their strength of preference for each question (Briggs & Nebes, 1975). This scoring system replaces the grouping system of Annett's original measurement and results in a continuum of handedness. Also, this scoring procedure attempts to better classify individuals of mixed handedness or ambidextrous. This modified version results in a continuous variable rather than a categorical variable; therefore, it can be more accurately compared to the continuous range of scores drawn from the EHI.

For the purposes of this study, both the Briggs and Nebes (1975) modified version of Annett’s Hand Preference Questionnaire and the Edinburgh Handedness Inventory will be used to assess hand preference. The EHI is widely used in psychological research; however, this measurement also has flaws; therefore, the Briggs and Nebes questionnaire will be used as an alternate form of assessing handedness. All data analyses will be conducted twice using both the EHI and Briggs and Nebes questionnaires. Additionally, future secondary analysis can be conducted to evaluate the comparative differences between these two measures. However, a statistical analysis comparing the two measures is out of the scope of the aims of this project and will therefore be conducted in the future.

Aims of the Proposed Study

The overall purpose of the present study was to gain further understanding of the relationship between hand dominance, as a continuous variable, and temporal variability in bimanual motor coordination. Previously, significant findings have supported the presence of a bimanual advantage when completing in-phase bimanual tasks compared to out-of-phase and unimanual tasks (Helmuth & Ivry, 1996; Drewing, Hennings, & Aschersleben, 2002; Studenka et al., 2014). On the contrary, Serrien (2008) found that participants had more temporal efficiency when executing unimanual tasks. Even though empirical evidence has supported the presence of a bimanual advantage, it is still worthy of further investigation to fully understand the potential advantages of various coordinated tasks. Additionally, a more in-depth understanding of bimanual coordination may add to the existing knowledge of motor deficits within clinical populations.

In addition, handedness can be further evaluated as a potential contributing factor to the variability observed in coordinated motor tasks. Recent behavioral findings suggest that individuals with strong or weak hand dominance may have varying performance on synchronized and asynchronized motor tasks (Kourtis et al., 2014); however, the exact relationship between handedness and motor coordination remains unclear. Handedness may be a vital moderator in the successful execution of various motor tasks, including bimanual coordination. Therefore, this project will attempt to expand upon the existing literature on handedness and bimanual coordination.

Specific Aim 1: To investigate the presence of a bimanual advantage in the execution of in-phase bimanual tapping tasks compared to other coordinated conditions in healthy young adults.

Hypothesis 1 (a): Individuals will perform with less efficiency, or greater temporal variability, on the unimanual tapping condition thanthe bimanual synchronized condition, which would further support the presence of a bimanual advantage.

Hypothesis 1 (b): Temporal variability will be larger in the out-of-phase bimanual condition than both the unimanual and synchronized bimanual conditions.

Specific Aim 2: To investigate the relationships between hand dominance and bimanual coordination in an adult population.

Hypothesis 2 (a): Individuals with strong hand dominance will perform with greater efficiency, or less temporal variability, on the unimanual and out-of-phase bimanual conditions than individuals with weak hand dominance.

Hypothesis 2 (b): Individuals with weak hand dominance will perform with greater efficiency, or less temporal variability, on the in-phase, bimanual condition than individuals with strong hand dominance.

Specific Aim 3: To explore the relationship between previous musical and athletic experience and motor coordination in an adult population.

Hypothesis 3 (a): Individuals that self-report previously participating in musical experience and/or athletic experience will perform with greater efficiency on each experimental tapping condition than individuals that report no extensive musical or athletic experience.

Research Design and Methodology

Participants

Participants for the present study include a sample of 56 young adults ranging in age from 18 to 39 (*M*=23.6, *SD*=6.3; 41 females). Seventy-three percent of participants were Caucasian, 14% were African American, 4% were Hispanic, 4% were Asian, and 5% belonged to other racial groups. In regard to musical and athletic experience, 60% had prior musical experience and 80% had prior athletic experience. Exclusionary criteria for the present study included any serious head injury or bone fracture, as these conditions may have confounded the participants' performance on coordinated motor tasks. Additionally, participants were excluded from the study if they had been diagnosed with a neurodevelopmental disorder (attention-deficit/ hyperactivity disorder, autism spectrum disorder, developmental coordination disorder, or learning disabilities). This exclusion is due to the fact that these disorders may result in motor impairments, difficulties reading, or difficulties focusing, which are each necessary functions for completing this proposed study (Bo et al., 2008; APA, 2013).

For the present study, participants were recruited through the posting of flyers (see Appendix A) in academic buildings at Eastern Michigan University and through advertisement on the SONA Systems experiment management system at Eastern Michigan University. The announcements posted called for healthy male and female volunteers between the ages of 18 and 40 with varying degrees of hand dominance who were interested in participating in a research study (titled Handedness and Bimanual Motor Coordination) about the effects of hand dominance on hand coordination tasks. Recruited participants were expected to have normal or corrected-to-normal vision. Before recruitment began, Institutional Review Board approval was obtained.

Procedure

For this study, undergraduate students at Eastern Michigan University were trained by the principal investigator to collect data. Training included learning the appropriate administration of all measures, practicing administration with the principal investigator, and administrating the measures to a research participant under supervision. Each participant completed all components of the study at Eastern Michigan University and the experiment took approximately 30 minutes to complete. Before beginning the testing procedures, participants were read and asked to sign an informed consent form (see Appendix B). The consent form was read aloud by the principal investigator or research assistant and signed by the participant.

Once participants agreed to participate by signing the informed consent, they completed a brief demographic and health history questionnaire (see Appendix C). Next participants were asked to complete two handedness inventories (see Appendix D and E) and a Grooved Pegboard Test. Finally, participants completed a tapping task guided by computer instructions to assess bimanual coordination. Participants received extra credit in their academic courses for completing the study; however, the amount of extra credit was professor and course dependent.

Measures

Questionnaire. Participants received a brief demographic and health history questionnaire that consisted of ten questions, such as age, history of vision impairments, and experience playing instruments (See Appendix C). Participants were encouraged to complete the questionnaire in its entirety. If a participant endorsed any exclusion criteria on the questionnaire, as stated previously, no further data was collected for that participant.

Handedness Inventories. The participant’s handedness was assessed by means of the Edinburgh Handedness Questionnaire (EHI) (Oldfield, 1971) and The Handedness Inventory modified from the Annett Hand Preference Questionnaire (Annett, 1970; Briggs & Nebes, 1975). In order to avoid bias, participants were asked to complete the two handedness questionnaires in random order. According to assigned participant codes, participants with even numbered codes completed the EHI first and participants with odd numbered codes completed The Handedness Inventory first.

The EHI is a 10-item self-report questionnaire assessing hand preference in everyday activities, such as writing, using a spoon, or opening a box lid (See Appendix D). Participants were asked to indicate their preference for each item with a check mark for either their right or left hand. If the participant's hand preference for that task is strong and they would definitively not use their opposite hand, they were instructed to place two check marks for the appropriate hand. The instructions provided also gave participants the option to indicate whether they complete a task equally with both their right and left hand, in which they placed one check mark in each box next to that item.

The items were scored by totaling the number of check marks in both the left and right columns. These totals were inserted into the formula below to produce a laterality quotient (Oldfield, 1971):

$$H = \left(\frac{R - L}{R + L}\right) * 100$$

In this formula, R is equal to the number of ticks totaled for the right hand and L is equal to the number of ticks totaled for the left hand. Laterality quotients can range from -100 to +100 in which -100 signifies complete sinistrality, or left-handedness, and +100 signifies complete dextrality, or right-handedness.

For the main purposes of this study, handedness was analyzed as a continuous variable. However, for additional analyses, handedness was also categorized into four groups according to the scores from the EHI: consistent right-handers, inconsistent right-handers, consistent left handers, and inconsistent left-handers. The consistent left-handers have scores ranging from -70 to -100, and consistent right-handers have scores ranging from +70 to +100. The inconsistent left-handers have scores ranging from -69 to 0, and consistent right-handers have scores ranging from 0 to +69. These ranges have been chosen to reflect those utilized in previous literature (Goyrnia & Egenter, 2000).

Additionally, participants were asked to complete The Handedness Inventory, which is a modified version of the Annett Hand Preference Questionnaire (Annett, 1970; Briggs & Nebes, 1975). The Handedness Inventory is a 12-item self-report questionnaire assessing hand preference in everyday activities, similar to those on the EHI (See Appendix E). Examples of questions on The Handedness Inventory include which hand is preferred to use a racquet, shovel, or deal cards. Each item was scored on a 5-point scale with “always” equal to two points, “usually” equal to one point, and “no preference” equal to zero points. Participants were asked to indicate their preference for each item and were instructed to place one check mark in one response box for each item.

In order to score The Handedness Inventory, the left-handed responses were scored with negative point values and the right-handed responses were scored with positive point values. Therefore, for the entire 12-item questionnaire participants could receive total scores ranging from -24 to +24. A score of -24 signifies complete sinistrality and a score of +24 signifies complete dextrality. For alternative analyses, handedness was grouped by left handed, mixed handed, and right handed using The Handedness Inventory. According to Briggs and Nebes (1975), the total score from the 12-item questionnaire can be divided by 3, which is reported as an arbitrary dividend by the authors. Therefore, those with scores -24 or less are in the left handed group, score between -13 and +13 are in the mixed handed group, and scores above +24 are in the right handed group.

Tapping Paradigm. For the finger tapping task, each participant was seated at a computer desk and visual stimuli were presented on the computer monitor. Participants were asked to distance themselves at an appropriate length from the computer monitor (approximately 24 inches) so that they could properly see the visual stimuli presented and comfortably reach the keyboard with their hands. The tapping task was written in E-Prime and took approximately 20 minutes to complete five experimental conditions. Instructions were provided before each experimental condition and participants did not receive feedback during the experiment. In order to counterbalance the order of presentation, the experimental tapping conditions were ordered randomly for each participant (See Appendix F for recording).

Each participant completed all five experimental conditions with their index fingers of either both (bimanual) or one (unimanual) hand: unimanual left, unimanual right, bimanual in-phase, bimanual right-lead out-of-phase, and bimanual left-lead out-of-phase. Conditions with a lead included a 180 millisecond delay relative to the leading finger. During the unimanual conditions, participants were asked to rest their inactive hand at the side of the keyboard. Each experimental condition consisted of five blocks of 12 trials with 180 millisecond inter-tap intervals. Participants were asked to press the “J” key with their right index finger and “F” key with their left index finger. For each condition, participants were instructed to fixate on a blue cross in a 32.5 cm x 27 cm white box on the computer screen. Blue ovals (height = 7 cm) will flash 4 cm from either side of the fixation cross to pace participants’ responses. The side of the presented oval corresponded with the participants tapping hand. See Appendix G for screen stills of the visual stimuli presented during the tapping paradigm.

In addition to the visually cued conditions, participants were asked to complete five blocks of 12 trials for each of the above mentioned experimental conditions without visual cues. After each visually cued trial, participants were asked to continue the tapping at the requested coordinated speed and format while fixating on only the blue cross in the middle of the screen. This required participants to use internal timing skills without any visual stimuli or feedback as they attempted to maintain the target interval. After 12 non-cued tapping responses, the trial ended.

Data Analysis

All data collected for this study were entered, coded, and double checked for errors before analyses was performed. All of the original copies of data are password protected on the lab computer or locked within a filing cabinet in the Cognitive Neuroscience Lab at Eastern Michigan University for future potential data checking. The analysis of the data collected by E-prime for the tapping task were performed in MATLAB, which included the mean, standard deviation, and the coefficient of variation for each block consisting of 12 trials. For the bimanual conditions, these values were calculated for both the right and left hands independently and the average difference between the right and left hand. These values were only calculated once for the respective hand in the unimanual conditions (e.g., right hand for right tapping condition). For analysis, all data were transferred to the SPSS software version 18.0 (SPSS Inc., Chicago). For data analysis, the following variables were entered and coded as dependent variables for each participant: Edinburgh Handedness Inventory laterality quotient (absolute value), The Handedness Inventory score (absolute value), mean standard deviation across five trials for each experimental tapping condition in milliseconds, and descriptive variables, including musical and athletic experience, sex, ethnicity, and age.

Specific Aim 1: *To investigate the presence of a bimanual advantage in the execution of in-phase bimanual tapping tasks compared to other coordinated conditions in healthy young adults.* Each hypothesis under Specific Aim 1 was analyzed using one-way analysis of variance (ANOVA). The independent variables for this analysis were the experimental conditions, including unimanual right, unimanual left, bimanual, right-lead out-of-phase, and left-lead out-of-phase. The dependent variable was the average standard deviation in response time in milliseconds for each condition. Post hoc comparisons using bonferroni corrections were performed when significant results were found in ANOVA. For these analyses, the significance level will be set at 0.05.

Specific Aim 2: *To investigate the relationships between hand dominance and bimanual coordination in an adult population.* The hypotheses under Specific Aim 2 were analyzed using correlational analyses to assess the relationship between handedness, as measured by The Handedness Inventory, and temporal variability for each experimental condition. The correlation coefficients for the five analyses would be compared using Fisher's Z-Test if significant correlations were found.

Alternatively, Specific Aim 2 was analyzed by making handedness a categorical variable instead of a continuous variable. A two-way ANOVA was utilized to assess handedness and each experimental tapping condition. The between-subject factor was the handedness group, as determined separately by the EHI and The Handedness Inventory, and the within-subject factor was the experimental tapping condition. The Tukey HSD post-hoc analysis was conducted following significant two-way ANOVA results.

Specific Aim 3: *To explore the relationship between previous musical and athletic experience and motor coordination in an adult population.* Aim 3 was analyzed using one-way analysis of variance (ANOVA). The analysis was run separately for both music and sports, and each analysis was conducted for each experimental condition. The independent variable for this analysis was the experimental groups, individuals with musical experience, individuals with athletic experience, individuals with no musical experience, and individuals with no athletic experience. The dependent variable was the average standard deviation in response time in milliseconds for each condition. The bonferroni post-hoc analysis was conducted following significant ANOVA results. For these analyses, the significance level was set at 0.05.

Results

Missing Data

For the present study, data was collected from 70 participants (ages 18 to 39 years); however, data for 14 participants were excluded. Three individuals participated in the study and received extra credit for their academic class; however, due to exceeding the age limit of 40, their data were not included in data analysis. Additionally, the tapping data were thoroughly assessed for each block within a condition for each participant. Data were assessed by hand and no statistical software was utilized to calculate missing data for each participant. If an individual was missing more than fifty percent of the data for more than two trials, their data was considered invalid for that condition. If a participant's data was considered invalid for any condition, their data was excluded from all five experimental conditions. In total, data from 11 participants were excluded from data analysis due to having invalid data for at least one experimental condition.

Descriptive Statistics

All participants completed the Edinburgh Handedness Inventory and The Handedness Inventory. According to the EHI, 40 participants were categorized as being right-handed (i.e., positive laterality quotient) and 16 as left-handed (i.e., negative laterality quotient). The participants were also separated into four groups based on the consistency of their handedness according to the EHI (see Table 1). The Handedness Inventory identified 41 participants as right-handed (i.e., positive value) and 15 as left-handed (i.e., negative value). Also, the participants were separated into three groups based on their handedness as reported by The Handedness Inventory (See Table 2). Correlational analysis of the two handedness measures revealed a positive correlation ($r_{(56)}$=0.941, $p < 0.01$) when categorizing right and left handers and a positive correlation (r(56)=0.69, $p < 0.01$) when categorizing participants based on strength of handedness (i.e. EHI and The Handedness Inventory scores as absolute values).

Table 1

Descriptive Statistics for Edinburgh Handedness Inventory

Variable	N
Consistent Right Hander (CRH)	23
Inconsistent Right Hander (IRH)	17
Consistent Left Hander (CLH)	8
Inconsistent Left Hander (ILH)	8

Note. CRH = 70 to 100; IRH = 0 to 69; CLH = -100 to -70; ICL = -69 to 0.

Table 2

Descriptive Statistics for The Handedness Inventory

Variable	N
Right-Handed	25
Mixed-Handed	19
Left-Handed	12

Note. Right Handed = 13 to 24; Left Handed = -24 to -13; Mixed Handed = -12 to 12.

Bimanual Advantage

Hypothesis 1a. It was hypothesized that individuals would have greater variability on the unimanual condition than the bimanual in-phase condition.

Consistency in tapping was measured by the average standard deviation across blocks within a condition. The variability in tapping was measured for the right hand, left hand, and the difference between hands for each bimanual condition and for the right hand or left hand for the unimanual conditions. In regards to only performance in the right hand, a one-way analysis of variance (ANOVA) yielded significant variation in temporal variability among the experimental tapping conditions, ($F_{(3,220)} = 6.39$, $p \leq 0.01$). The means and standard deviations for each condition are presented in Table 3. Post hoc comparisons using the LSD test revealed the bimanual in-phase and unimanual right conditions differed significantly ($p < 0.01$) for the right hand (See Table 4). Also, bivariate correlations revealed a significant correlation for right hand performance between the unimanual right and bimanual in-phase conditions ($p < 0.05$). These results suggest that the unimanual condition resulted in greater temporal variability than the bimanual in-phase condition, supporting the presence of a bimanual advantage.

Within left hand performance, a one-way ANOVA yielded significant variation in temporal variation among the experimental conditions, ($F_{(3,220)}=3.35$, $p = 0.02$). The means and standard deviations for the experimental conditions are presented in Table 3. Post hoc analysis using the LSD test revealed that the bimanual in-phase and unimanual left conditions differed significantly ($p < 0.05$) (See Table 4). Also, results from bivariate correlations revealed a significant correlation for left hand performance between the unimanual left and bimanual in-phase conditions ($p<0.001$). Together, these results also support the presence of a bimanual advantage, as the unimanual left condition resulted in greater temporal variability compared to the bimanual in-phase condition.

Table 3

Descriptive Statistics for Temporal Variability

Condition	Mean (ms.)	Standard Deviation (ms.)
Between Hands		
Bimanual In-phase	10.46	6.84
Right-lead Out-of-phase	41.72	20.21
Left-lead Out-of-phase	40.99	14.62
Right Hand		
Bimanual In-Phase	79.47	39.60
Right-lead Out-of-phase	106.55	49.79
Left-lead Out-of-phase	83.99	49.79
Unimanual Right	113.52	55.24
Left Hand		
Bimanual In-Phase	93.63	55.71
Right-lead Out-of-phase	84.71	51.00
Left-lead Out-of-phase	106.41	59.13
Unimanual Left	116.22	60.69

Note. Means and standard deviations were calculated across the sample.

Table 4

Post Hoc (LSD) Analysis of Variability Between Experimental Conditions

Condition		Mean Difference	Significance
Between Hands			
Bimanual In-phase	Left-Lead Out-of-Phase	-30.53	< 0.001**
Bimanual In-phase	Right-Lead Out-of-Phase	-31.26	< 0.001**
Right-Lead Out-of-Phase	Left-Lead Out-of-Phase	-0.73	0.796
Right Hand			
Bimanual In-phase	Left-Lead Out-of-Phase	-4.53	0.962
Bimanual In-phase	Right-Lead Out-of-Phase	-27.08	0.021*
Bimanual In-phase	Unimanual Right	-34.06	0.002**
Left-Lead Out-of-Phase	Right-Lead Out-of-Phase	-22.55	0.077
Left-Lead Out-of-Phase	Unimanual Right	-29.53	0.010**
Right-Lead Out-of-Phase	Unimanual Right	-6.98	0.878
Left Hand			
Bimanual In-phase	Left-Lead Out-of-Phase	-12.78	0.235
Bimanual In-phase	Right-Lead Out-of-Phase	8.92	0.406
Bimanual In-phase	Unimanual Left	-22.59	0.036*
Left-Lead Out-of-Phase	Right-Lead Out-of-Phase	21.70	0.044*
Left-Lead Out-of-Phase	Unimanual Left	-9.81	0.361
Right-Lead Out-of-Phase	Unimanual Left	-31.51	0.004**

*$p<0.05$ **$p<0.01$

Hypothesis 1b. It was hypothesized individuals would show the greatest amount of temporal variability on the out-of-phase bimanual conditions compared to the unimanual and bimanual synchronized conditions.

In regard to the difference in performance between hands, a one-way ANOVA revealed significant variation between the experimental conditions, ($F_{(2,165)} = 79.91$, $p < 0.001$). The means and standard deviations are presented in Table 3. Post hoc comparisons using the LSD test revealed that the bimanual and out-of-phase conditions differed significantly ($p \leq 0.01$) in regards to the between hands difference, with the out-of-phase conditions having greater temporal variability than the bimanual synchronized condition (See Table 4). These results suggest that participants performed more variably on the out-of-phase bimanual conditions than the bimanual synchronized condition, which is consistent with the proposed hypothesis.

Within right hand performance, a one-way ANOVA revealed significant variation between the experimental conditions ($F_{(3,220)}=6.39$, $p \leq 0.001$). Means and standard deviations for the experimental conditions are presented in Table 3. Post hoc analyses revealed a significant difference between performances on the right-lead out-of-phase condition and the bimanual in-phase condition ($p < 0.05$), but no significant difference with the unimanual right condition (See Table 4). Furthermore, participants did perform significantly more variable on the right-lead out-of-phase condition than the bimanual in-phase condition, but not the unimanual right condition. However, bivariate correlations did reveal a significant correlation between the right-lead out-of-phase and unimanual right conditions ($p<0.01$) when evaluating performance in the right hand. Together, these results suggest that the right-lead out-of-phase condition was more variable compared to the bimanual in-phase and unimanual right conditions within right hand performance, which is consistent with the proposed hypothesis. In addition, post hoc analyses revealed a significant difference between performances on the left-lead out-of-phase condition with unimanual left tapping ($p < 0.01$), but no significant difference with the bimanual in-phase condition (See Table 4). However, the unimanual condition performed more variably compared to the left-lead out-of-phase condition, which does not support the proposed hypothesis. Notably, post hoc comparisons revealed a significant difference between the right-lead out-of-phase and left-lead out-of-phase conditions ($p<0.05$), see Table 4. Together, these results suggest that the proposed hypothesis was supported in right hand performance when considering the right-lead out-of-phase condition, but the hypothesis was not supported when considering right hand performance in the left-lead out-of-phase condition.

Within left hand performance, a one-way ANOVA revealed significant variation between experimental conditions ($F_{(3,220)}=3.35$, $p<0.05$). Means and standard deviations are presented in Table 3. Post hoc analyses revealed a significant difference between performances on the right-lead out-of-phase condition with the unimanual left tapping condition ($p < 0.01$), but no significant difference with the bimanual in-phase condition (See Table 4). However, the unimanual left condition performed more variably than the right-lead out-of-phase condition. For left hand performance, post hoc comparisons revealed no significant differences between right-lead out-of-phase and the bimanual in-phase and unimanual left conditions (See Table 4). Additionally, post hoc comparisons revealed a significant difference between the right-lead out-of-phase and left-lead out-of-phase conditions ($p<0.05$), see Table 4. These results suggest that the proposed hypothesis was not supported when considering left hand performance.

Coordination and Handedness

Hypothesis 2a and 2b: It was hypothesized that individuals with strong hand dominance would perform with greater efficiency on the unimanual and out-of-phase conditions, while those with weak hand dominance would perform more efficiently on the bimanual synchronized condition.

Handedness scores were transformed for both the EHI and The Handedness Inventory to the absolute values to represent handedness as strong and weak handedness versus right or left-handed. Bivariate correlations revealed no significant differences between both hand dominance questionnaires and the experimental tapping conditions, as shown in Table 5. These results suggest the degree of handedness, weak versus strong, was not significantly related to performance across the tapping conditions. Additionally, bivariate correlations of pre-transformed handedness scores revealed no significant differences between both hand dominance questionnaires and the tapping consistency for all experimental conditions, as shown in Table 6, with the exception of a significant correlation between performance on the unimanual left condition and handedness scores on the EHI ($p<0.05$) and The Handedness Inventory ($p<0.01$). In other words, lower EHI scores, indicating strong left hand dominance, resulted in more temporal variability on the unimanual left conditions.

Table 5

Correlation Coefficients for Handedness (Strong Handedness vs. Weak Handedness) and Coordination Measures

	EHI	The Handedness Inventory
EHI	1.00	
The Handedness Inventory	0.69**	1.00
Bimanual – Between hands	0.05	0.12
Bimanual – Right hand	-0.08	-0.04
Bimanual – Left hand	-0.21	-0.12
Right-lead – Between hands	0.06	0.02
Right-lead – Right hand	-0.03	-0.09
Right-lead – Left hand	-0.14	-0.04
Left-lead – Between hands	-0.15	-0.01
Left-lead – Right hand	-0.05	-0.09
Left-lead – Left hand	-0.08	-0.05
Right tapping – Right hand	0.00	0.03
Left tapping – Left hand	-0.02	-0.02

Note. The Edinburgh Handedness Inventory laterality quotients and The Handedness Inventory scores were transformed to absolute values to capture strong versus weak handedness before data analysis was conducted.

**$p<0.01$

Table 6

Correlation Coefficients for Handedness (Extreme Right Handed vs. Extreme Left-handed) and Coordination Measures

	EHI	The Handedness Inventory
EHI	1.00	
The Handedness Inventory	0.94**	1.00
Bimanual – Between hands	0.05	0.10
Bimanual – Right hand	0.17	0.18
Bimanual – Left hand	0.08	0.12
Right-lead – Between hands	0.15	0.12
Right-lead – Right hand	-0.01	-0.03
Right-lead – Left hand	-0.08	-0.10
Left-lead – Between hands	-0.09	-0.08
Left-lead – Right hand	-0.04	-0.07
Left-lead – Left hand	0.19	0.20
Right tapping	0.12	0.05
Left tapping	0.34*	0.37**

*$p<0.05$ **$p<0.01$

EHI Categorical Analysis. Alternative analyses were conducted with handedness as a categorical variable. In regard to EHI, the strong-handed participants were assessed by combining the consistent right handers and consistent left handers. Similarly, the weak-handed participants were assessed by combining the inconsistent left handers and inconsistent right-handers.

It was hypothesized that participants with strong hand dominance would not display a bimanual advantage and perform with greater temporal variability on the bimanual synchronized condition compared to the unimanual and out-of-phase conditions. The means and standard deviations for each experimental condition for the strong-handed participants are presented in Table 7. For the strong-handed group (n=31), one-way ANOVA results revealed significant variation between the experimental conditions for performance between hands ($F_{(2,90)} = 39.84$, $p < 0.001$), in the right hand ($F_{(3,120)}=4.81$, $p < 0.01$), and in the left hand ($F_{(3,120)} = 3.11$, $p < 0.05$). Post hoc comparisons using the LSD test revealed the bimanual in-phase and out-of-phase conditions differed significantly ($p \leq 0.001$) in regard to the between hands difference, with the out-of-phase conditions having greater temporal variability than the bimanual in-phase condition (See Table 8). This result is inconsistent with the proposed hypothesis, as strong-handed individuals were expected to perform more variably on the bimanual in-phase condition. For right hand performance, post hoc comparisons revealed the bimanual in-phase condition differed significantly with the right-lead out-of-phase condition ($p < 0.05$) and the unimanual right condition ($p<0.01$), with the right-lead out-of-phase and unimanual right conditions having greater temporal variability than the bimanual in-phase condition. Also, in the right hand performance, post hoc comparisons revealed the left-lead out-of-phase condition differed significantly with the right-lead out-of-phase condition ($p <0.05$) and the unimanual right condition ($p < 0.01$), with the right-lead out-of-phase and unimanual right conditions having greater temporal variability than the left-lead out-of-phase condition. For the left hand performance, post hoc comparisons revealed the unimanual left condition differed significantly than the bimanual in-phase ($p<0.01$) and right-lead out-of-phase ($p<0.05$) conditions, with the unimanual left condition having greater temporal variability than the bimanual in-phase and right-lead out-of-phase conditions. Overall, these results revealed that the bimanual synchronized condition did not result in the greatest amount of variability. The bimanual advantage was present within the strong-handed participants for both right and left hand performance, which is inconsistent with the proposed hypothesis.

Table 7

Descriptive Statistics of Temporal Variability (ms.) for Strong-Handed Participants (EHI)

	Between Hands		Left Hand		Right Hand	
	m	*SD*	*m*	*SD*	*m*	*SD*
Bimanual In-phase	9.72	6.97	79.74	34.68	74.68	29.56
Left-Lead Out-of-Phase	38.60	12.28	102.07	61.52	79.43	56.95
Right-Lead Out-of-Phase	42.89	23.68	83.72	49.55	106.57	52.60
Unimanual			113.63	51.15	115.45	58.70

Table 8

Post Hoc (LSD) Analysis of Variability Between Experimental Conditions for Strong-Handed Participants (EHI)

Condition		Mean Difference	Significance
Between Hands			
Bimanual In-phase	Left-Lead Out-of-Phase	28.88	0.000**
Bimanual In-phase	Right-Lead Out-of-Phase	33.17	0.000**
Right-Lead Out-of-Phase	Left-Lead Out-of-Phase	4.29	0.291
Right Hand			
Bimanual In-phase	Left-Lead Out-of-Phase	4.75	0.714
Bimanual In-phase	Right-Lead Out-of-Phase	31.89	0.015*
Bimanual In-phase	Unimanual Right	40.77	0.002**
Left-Lead Out-of-Phase	Right-Lead Out-of-Phase	27.14	0.038*
Left-Lead Out-of-Phase	Unimanual Right	36.02	0.006**
Right-Lead Out-of-Phase	Unimanual Right	8.88	0.493
Left Hand			
Bimanual In-phase	Left-Lead Out-of-Phase	22.33	0.082
Bimanual In-phase	Right-Lead Out-of-Phase	3.98	0.755
Bimanual In-phase	Unimanual Left	33.89	0.009**
Left-Lead Out-of-Phase	Right-Lead Out-of-Phase	18.35	0.152
Left-Lead Out-of-Phase	Unimanual Left	11.56	0.366
Right-Lead Out-of-Phase	Unimanual Left	29.91	0.020*

*$p<0.05$ **$p<0.01$

It was hypothesized that weak-handed participants would perform with greater temporal variability on the unimanual and out-of-phase conditions compared to the bimanual synchronized condition displaying a strong bimanual advantage. The means and standard deviations for each experimental condition for the weak-handed participants (n=25) are presented in Table 9. For the weak handed group, one-way ANOVA results revealed significant variation between the experimental conditions for performance between hands, ($F_{(2,72)}$=42.49, p<0.001). Post hoc comparisons using the LSD test revealed the bimanual in-phase and out-of-phase conditions differed significantly ($p \leq 0.001$) in regards to the between hands difference, with the out-of-phase conditions having greater temporal variability than the bimanual synchronized condition (See Table 10). These results are consistent with the proposed hypothesis. One-way ANOVA results revealed no significant variation between the experimental conditions for performance in the right hand ($F_{(3,96)}$=1.69, p=0.17) or the left hand ($F_{(3,96)}$=1.299, p=0.28). These results suggest the bimanual advantage was not present in the weak-handed group of participants for both the right and left hand performance, which is inconsistent with the proposed hypothesis.

Table 9

Descriptive Statistics of Temporal Variability (ms.) for Weak Handed Groups (EHI)

	Between Hands		Left Hand		Right Hand	
	m	*SD*	*m*	*SD*	*m*	*SD*
Bimanual In-phase	11.37	6.71	110.86	71.07	85.40	49.34
Left-Lead Out-of-Phase	43.94	16.89	111.80	56.81	89.65	44.63
Right-Lead Out-of-Phase	40.26	15.22	85.94	53.74	106.51	47.14
Unimanual			119.44	71.77	111.13	51.73

Table 10

Post Hoc (LSD) Analysis of Variability between Experimental Conditions for Weak Handed/Ambidextrous Participants (EHI)

Condition		Mean Difference	Significance
Between Hands			
Bimanual In-phase	Left-Lead Out-of-Phase	-32.57	0.000**
Bimanual In-phase	Right-Lead Out-of-Phase	-28.90	0.000**
Right Lead Out-of-Phase	Left-Lead Out-of-Phase	3.68	0.345
Right Hand			
Bimanual In-phase	Left-Lead Out-of-Phase	-4.25	0.756
Bimanual In-phase	Right-Lead Out-of-Phase	-21.11	0.125
Bimanual In-phase	Unimanual Right	-25.73	0.063
Left-Lead Out-of-Phase	Right-Lead Out-of-Phase	-16.86	0.220
Left-Lead Out-of-Phase	Unimanual Right	-21.48	0.119
Right-Lead Out-of-Phase	Unimanual Right	-4.62	0.736
Left Hand			
Bimanual In-phase	Left-Lead Out-of-Phase	-0.94	0.959
Bimanual In-phase	Right-Lead Out-of-Phase	24.92	0.171
Bimanual In-phase	Unimanual Left	-8.57	0.636
Left-Lead Out-of-Phase	Right-Lead Out-of-Phase	25.85	0.156
Left-Lead Out-of-Phase	Unimanual Left	-7.64	0.673
Right-Lead Out-of-Phase	Unimanual Left	-33.49	0.067

$*p<0.05$ $**p<0.01$

Due to the above results, distribution of the data, and empirical curiosity, strong right handers and strong left handers were assessed separately utilizing one-way ANOVAs. As previously mentioned, it was hypothesized that strong-handed individuals would perform with greater temporal variability on the bimanual synchronized condition than the unimanual and out-of-phase conditions and would not display a strong bimanual advantage. The means and standard deviations for each experimental condition for the strong right-handed participants (n=23) are presented in Table 11. For the strong right-handed group, one-way ANOVA results revealed significant variation between the experimental conditions for performance between hands ($F_{(2,66)}=25.89$, $p<0.001$), in the right hand ($F_{(3,88)}=3.27$, $p<0.05$), and in the left hand ($F_{(3,88)}=4.26$, $p<0.01$). Post hoc comparisons using the LSD test revealed the bimanual in-phase and out-of-phase conditions differed significantly ($p\leq0.001$) in regards to the between hands difference, with the out-of-phase conditions having greater temporal variability than the bimanual in-phase condition (See Table 12). For right hand performance, post hoc comparisons revealed the unimanual right condition differed significantly with the bimanual in-phase ($p<0.01$) and left-lead out-of-phase ($p<0.05$) conditions, with the unimanual condition having greater temporal variability than the bimanual in-phase and left-lead out-of-phase conditions. For the left hand performance, post hoc comparisons revealed the unimanual left condition differed significantly than the bimanual in-phase ($p<0.01$) and right-lead out-of-phase ($p<0.01$) conditions, with the unimanual left condition having greater temporal variability than the bimanual in-phase and right-lead out-of-phase conditions. These results suggest that the bimanual advantage was present in both right and left hand performance for strong right handers, which, again, is inconsistent with the proposed hypothesis.

Table 11

Descriptive Statistics of Temporal Variability (ms.) for Strong Right-Handed Group (EHI)

	Between Hands		Left Hand		Right Hand	
	m	*SD*	*m*	*SD*	*m*	*SD*
Bimanual In-phase	9.95	7.54	80.23	33.41	76.80	30.30
Left-Lead Out-of-Phase	37.23	12.13	110.12	67.60	81.97	63.14
Right-Lead Out-of-Phase	44.16	25.84	84.43	53.91	105.00	56.30
Unimanual			128.11	48.89	119.84	57.73

Table 12

Post Hoc (LSD) Analysis of Variability Between Experimental Conditions for Strong Right Handed Participants (EHI)

Condition		Mean Difference	Significance
Between Hands			
Bimanual In-phase	Left-Lead Out-of-Phase	27.28	0.000**
Bimanual In-phase	Right-Lead Out-of-Phase	34.21	0.000**
Right-Lead Out-of-Phase	Left-Lead Out-of-Phase	6.92	0.358
Right Hand			
Bimanual In-phase	Left-Lead Out-of-Phase	5.17	0.744
Bimanual In-phase	Right-Lead Out-of-Phase	28.20	0.077
Bimanual In-phase	Unimanual Right	43.04	0.008**
Left-Lead Out-of-Phase	Right-Lead Out-of-Phase	23.03	0.147
Left-Lead Out-of-Phase	Unimanual Right	37.87	0.018*
Right-Lead Out-of-Phase	Unimanual Right	14.84	0.349
Left Hand			
Bimanual In-phase	Left-Lead Out-of-Phase	29.89	0.056
Bimanual In-phase	Right-Lead Out-of-Phase	4.20	0.786
Bimanual In-phase	Unimanual Left	47.88	0.003**
Left-Lead Out-of-Phase	Right-Lead Out-of-Phase	25.69	0.100
Left-Lead Out-of-Phase	Unimanual Left	17.99	0.247
Right-Lead Out-of-Phase	Unimanual Left	43.68	0.006**

*$p<0.05$ **$p<0.01$

Strong left-handed participants (n=8) were also assessed and their means and standard deviations are presented in Table 13. For the strong left handed group, one-way ANOVA results revealed significant variation between the experimental conditions for between hands performance, $F_{(2,21)}=17.31$, $p\leq0.001$. Post hoc comparisons using the LSD test revealed the bimanual in-phase and out-of-phase conditions differed significantly ($p\leq0.001$) in regards to the between hands difference, with the out-of-phase conditions having greater temporal variability than the bimanual in-phase condition (See Table 14). One-way ANOVA results revealed no significant variation between the experimental conditions for performance in the right hand ($F_{(3,28)}=0.11$,$p=0.96$) and the left hand ($F_{(3,28)}=1.84$,$p=0.16$).

Table 13

Descriptive Statistics of Temporal Variability (ms.) for Strong Left-Handed Group (EHI)

	Between Hands		Left Hand		Right Hand	
	m	*SD*	*m*	*SD*	*m*	*SD*
Bimanual	9.06	5.37	78.34	40.55	68.59	28.31
Left-Lead Out-of-Phase	42.55	12.62	78.93	32.20	72.14	35.87
Right-Lead Out-of-Phase	39.25	16.85	81.68	37.19	111.10	43.17
Unimanual			72.00	32.16	102.84	63.64

Table 14

Post Hoc (LSD) Analysis of Variability Between Experimental Conditions for Strong Left-Handed Participants (EHI)

Condition		Mean Difference	Significance
Between Hands			
Bimanual In-phase	Left Lead Out-of-Phase	33.48	0.000
Bimanual In-phase	Right Lead Out-of-Phase	30.19	0.000
Right-Lead Out-of-Phase	Left Lead Out-of-Phase	3.29	0.860
Right Hand			
Bimanual In-phase	Left-Lead Out-of-Phase	3.55	0.875
Bimanual In-phase	Right-Lead Out-of-Phase	42.51	0.068
Bimanual In-phase	Unimanual Right	34.25	0.137
Left-Lead Out-of-Phase	Right-Lead Out-of-Phase	38.96	0.092
Left-Lead Out-of-Phase	Unimanual Right	30.70	0.181
Right-Lead Out-of-Phase	Unimanual Right	8.26	0.715
Left Hand			
Bimanual In-phase	Left-Lead Out-of-Phase	0.59	0.974
Bimanual In-phase	Right-Lead Out-of-Phase	3.34	0.853
Bimanual In-phase	Unimanual Left	6.33	0.726
Left-Lead Out-of-Phase	Right-Lead Out-of-Phase	2.75	0.879
Left-Lead Out-of-Phase	Unimanual Left	6.92	0.701
Right-Lead Out-of-Phase	Unimanual Left	9.67	0.592

*$p<0.05$ **$p<0.01$

All together, these results revealed similarities between the strong left-handed group and the weak-handed group. Both groups revealed no significant variations across experimental conditions when considering right or left hand performance. Furthermore, no significant variations were observed between the unimanual and bimanual in-phase conditions for the right or left hand in either the strong left-handed and weak-handed groups, indicating there was no bimanual advantage present. On the other hand, the results revealed the strong right handers had a different pattern of performance. For instance, there was a significant difference in performance between the bimanual in-phase and unimanual conditions for both right and left hand performance, supporting the presence of a bimanual advantage. Due to the apparent differences between the strong right-handed group and the weak- and left-handed participants, a follow up analysis was conducted assessing the relationship between tapping performance and handedness, with handedness categorized into two groups: strong right handers and strong left/weak handers.

A two-way ANOVA was conducted to evaluate the interaction effect on tapping variability between tapping conditions and handedness, with handed groups (strong right handers vs. combined strong left/weak handers) as a between-subject factor and conditions as a within-subject factor. Results revealed no significant interaction for performance between hands ($F_{(1.73, 93.35)}=2.17$, $p =0.13$), in the right hand ($F_{(2.84,153.06)}=0.40$, $p=0.74$), and in the left hand ($F_{(2.59,139.92)}=2.16$, $p=0.10$). The main effect for tapping was significant for performance between hands ($F_{(1.73,93.35)}=99.95$, $p \leq 0.001$), in the right hand ($F_{(2.83,153.06)}=9.30$, $p \leq 0.001$), and in the left hand ($F_{(2.59,139.92)}=6.11$, $p < 0.01$). Due to these significant main effects, a one-way ANOVA was conducted to assess performance across the tapping conditions within the combined group of strong left- and weak-handed participants.

The means and standard deviations for each experimental condition for the combined handedness group (n=33) are presented in Table 15. For the combined group, one-way ANOVA results revealed significant variation between the experimental conditions for performance between hands ($F_{(2,96)}=60.88$,$p\leq0.001$) and in the right hand ($F_{(3,128)}=3.148$,$p<0.05$). Post hoc comparisons using the LSD test revealed the bimanual in-phase and out-of-phase conditions differed significantly ($p \leq 0.001$) in regards to the between hands difference, with the out-of-phase conditions having greater temporal variability than the bimanual in-phase condition (See Table 16). For right hand performance, post hoc comparisons revealed the bimanual in-phase condition differed significantly with the right-lead out-of-phase ($p<0.05$) and the unimanual right ($p<0.05$) conditions, with the right-lead out-of-phase and unimanual right conditions having greater temporal variability than the bimanual in-phase condition. Also, the left-lead out-of-phase and unimanual right conditions differed significantly ($p<0.05$) in regards to the right hand performance, with the unimanual right condition having greater temporal variability than the left-lead out-of-phase condition. One-way ANOVA results revealed no significant variation between the experimental conditions for performance in the left hand, $F_{(3,128)}=3.15$, $p=0.41$.These results suggest that the bimanual advantage was present for the combined group in right hand performance, but it was not present in the left hand performance.

Table 15

Descriptive Statistics of Temporal Variability (ms.) for the Combined Strong Left-Handed and Weak Handed Participants (EHI)

	Between Hands		Left Hand		Right Hand	
	m	*SD*	*m*	*SD*	*m*	*SD*
Bimanual In-phase	10.81	6.41	102.98	65.94	81.32	45.33
Left-Lead Out-of-Phase	43.60	15.78	103.83	53.40	85.40	42.82
Right-Lead Out-of-Phase	40.02	15.36	84.91	49.72	107.62	45.59
Unimanual			107.94	67.20	109.12	53.90

Table 16

Post Hoc (LSD) Analysis of Variability Between Experimental Conditions for Strong Left-Handed and Weak-Handed Participants (EHI)

Condition		Mean Difference	Significance
Between Hands			
Bimanual In-phase	Left-Lead Out-of-Phase	32.80	0.000**
Bimanual In-phase	Right-Lead Out-of-Phase	29.21	0.000**
Right-Lead Out-of-Phase	Left-Lead Out-of-Phase	3.59	0.274
Right Hand			
Bimanual In-phase	Left-Lead Out-of-Phase	4.08	0.725
Bimanual In-phase	Right-Lead Out-of-Phase	26.30	0.025*
Bimanual In-phase	Unimanual Right	27.80	0.018*
Left-Lead Out-of-Phase	Right-Lead Out-of-Phase	22.22	0.058
Left-Lead Out-of-Phase	Unimanual Right	23.72	0.043*
Right-Lead Out-of-Phase	Unimanual Right	1.50	0.897
Left Hand			
Bimanual In-phase	Left-Lead Out-of-Phase	0.85	0.954
Bimanual In-phase	Right-Lead Out-of-Phase	15.07	0.220
Bimanual In-phase	Unimanual Left	4.96	0.736
Left-Lead Out-of-Phase	Right-Lead Out-of-Phase	18.92	0.199
Left-Lead Out-of-Phase	Unimanual Left	4.11	0.780
Right-Lead Out-of-Phase	Unimanual Left	23.03	0.119

*$p<0.05$ **$p<0.01$

The Handedness Inventory Categorical Analysis. Similar analyses were performed using The Handedness Inventory to group three handed groups. The strong-handed participants were assessed first by combining the right-handed and left-handed groups. The weak-handed participants were assessed by analyzing the mixed handedness group.

It was hypothesized that participants with strong hand dominance would not display a bimanual advantage and perform with less temporal variability on the unimanual and out-of-phase conditions compared to the bimanual synchronized condition. The means and standard deviations for each experimental condition for the strong handed group (n=37) are presented in Table 17. For the strong handed participants, one-way ANOVA results revealed significant variation between the experimental conditions for performance between hands ($F_{(2,108)}$=68.01,

$p \leq 0.001$) and in the right hand ($F_{(3,144)}=4.88$, $p < 0.01$) similar to EHI results. Performance within the right hand, according to The Handedness Inventory, differed slightly from right hand performance when using EHI. For instance, the right-lead out-of-phase condition was not significantly more variable than the left-lead out-of-phase and bimanual in-phase conditions as was seen with the EHI (See Table 18). For left hand performance, one-way ANOVA results revealed no significant variation between the experimental groups ($F_{(3,144)}=2.50$, $p = 0.06$), and this relationship was significant for the EHI. Also, in The Handedness Inventory, post hoc comparisons of left hand performance revealed the right-lead out-of-phase and unimanual right conditions differed significantly with the unimanual right condition having greater temporal variability (See Table 18). This relationship was not significant in the EHI. Overall, these results were consistent with those for the EHI in that the bimanual advantage was present for right hand performance and the out-of-phase condition resulted in greater variability for between hands performance than the bimanual in-phase condition; however, these results are not consistent with the proposed hypothesis for strong-handed individuals. Notably, The Handedness Inventory did not reveal a bimanual advantage in left hand performance as was seen with the EHI.

Table 17

Descriptive Statistics of Temporal Variability (ms.) for the Strong-Handed Participants (The Handedness Inventory)

	Between Hands		Left Hand		Right Hand	
	m	*SD*	*m*	*SD*	*m*	*SD*
Bimanual In-phase	11.14	7.79	89.25	58.82	79.30	45.25
Left-Lead Out-of-Phase	42.16	15.39	101.00	49.76	80.91	36.01
Right-Lead Out-of-Phase	40.06	13.89	81.80	45.61	99.87	40.30
Unimanual			113.91	60.53	113.67	56.59

Table 18

Post Hoc (LSD) Analysis of Variability Between Experimental Conditions for Strong-Handed Participants (The Handedness Inventory)

Condition		Mean Difference	Significance
Between Hands			
Bimanual In-phase	Left-Lead Out-of-Phase	31.02	0.000**
Bimanual In-phase	Right-Lead Out-of-Phase	28.93	0.000**
Right-Lead Out-of-Phase	Left-Lead Out-of-Phase	2.10	0.761
Right Hand			
Bimanual In-phase	Left-Lead Out-of-Phase	1.60	0.879
Bimanual In-phase	Right-Lead Out-of-Phase	20.57	0.052
Bimanual In-phase	Unimanual Right	34.36	0.001**
Left-Lead Out-of-Phase	Right-Lead Out-of-Phase	18.97	0.073
Left-Lead Out-of-Phase	Unimanual Right	32.76	0.002**
Right-Lead Out-of-Phase	Unimanual Right	13.80	0.191
Left Hand			
Bimanual In-phase	Left-Lead Out-of-Phase	11.74	0.351
Bimanual In-phase	Right-Lead Out-of-Phase	7.46	0.554
Bimanual In-phase	Unimanual Left	24.66	0.052
Left-Lead Out-of-Phase	Right-Lead Out-of-Phase	19.20	0.129
Left-Lead Out-of-Phase	Unimanual Left	12.92	0.306
Right-Lead Out-of-Phase	Unimanual Left	32.12	0.012*

*$p<0.05$ **$p<0.01$

It was also hypothesized that participants with weak handedness would perform with greater variability on the unimanual and out-of-phase conditions compared to the bimanual in-phase condition, which would support the presence of a bimanual advantage. The means and standard deviations for each experimental condition for the weak-handed participants, or mixed handed group, (n=19) are presented in Table 19. For the weak-handed participants, one-way ANOVA results revealed significant variation between the experimental groups for between hand performance, $F_{(2,54)}=20.14$, $p\leq0.001$. Similar to the EHI, post hoc comparisons revealed the out-of-phase conditions resulted in greater variability than the bimanual in-phase condition (See Table 20). Also similar to the EHI, one-way ANOVA results revealed no significant variation between the experimental groups for performance in the left hand ($F_{(3,72)}=0.095$, $p=0.42$) and in the right hand ($F_{(3,72)}=2.05$, $p=0.12$). Unlike the EHI, post hoc comparisons revealed the right-lead out-of-phase condition was significantly more variable than the bimanual in-phase condition ($p<0.05$) in right hand performance (See Table 20). Altogether, these results suggest that the bimanual advantage was not present for the weak handed participants in either left or right hand performance, which is inconsistent with the proposed hypothesis. These results are consistent with those seen in weak-handed participants according to the EHI.

Table 19

Descriptive Statistics of Temporal Variability (ms.) for the Weak (Mixed) Handed Participants (The Handedness Inventory)

	Between Hands		Left Hand		Right Hand	
	m	*SD*	*m*	*SD*	*m*	*SD*
Bimanual In-phase	9.13	4.33	102.17	49.47	79.78	26.38
Left-Lead Out-of-Phase	38.69	13.09	116.96	74.52	90.00	74.10
Right-Lead Out-of-Phase	44.94	29.08	90.39	61.11	119.54	63.68
Unimanual			120.72	62.41	113.24	54.05

Table 20

Post Hoc (LSD) Analysis of Variability Between Experimental Conditions for Weak (Mixed) Handed Participants (The Handedness Inventory)

Condition		Mean Difference	Significance
Between Hands			
Bimanual In-phase	Left-Lead Out-of-Phase	29.57	0.000
Bimanual In-phase	Right-Lead Out-of-Phase	35.81	0.000
Right-Lead Out-of-Phase	Left-Lead Out-of-Phase	6.24	0.305
Right Hand			
Bimanual In-phase	Left-Lead Out-of-Phase	10.22	0.585
Bimanual In-phase	Right-Lead Out-of-Phase	39.76	0.036
Bimanual In-phase	Unimanual Right	33.46	0.076
Left-Lead Out-of-Phase	Right-Lead Out-of-Phase	29.84	0.117
Left-Lead Out-of-Phase	Unimanual Right	23.81	0.216
Right-Lead Out-of-Phase	Unimanual Right	6.30	0.736
Left Hand			
Bimanual In-phase	Left-Lead Out-of-Phase	14.80	0.468
Bimanual In-phase	Right-Lead Out-of-Phase	11.78	0.563
Bimanual In-phase	Unimanual Left	15.55	0.363
Left-Lead Out-of-Phase	Right-Lead Out-of-Phase	26.57	0.194
Left-Lead Out-of-Phase	Unimanual Left	3.75	0.854
Right-Lead Out-of-Phase	Unimanual Left	30.33	0.139

$^*p<0.05$ $^{**}p<0.01$

Similar to the EHI, strong right handers and strong left handers were assessed separately for The Handedness Inventory. The means and standard deviations for each experimental condition for the right handed group (n=25) are presented in Table 21. For the right-handed group, one-way ANOVA results revealed significant variation between the experimental groups for performance between hands ($F(2,72)=42.37$, $p \leq 0.001$), in the right hand ($F(3,96)=3.46$, $p<0.05$) and in the left hand ($F(3,96)=4.35$, $p<0.01$). Post hoc comparisons for The Handedness Inventory revealed identical results as seen with the EHI (See Table 22). However, in left hand performance, the left-lead out-of-phase condition was significantly more variable ($p<0.05$) compared to the right-lead out-of-phase condition (See Table 22). This significant relationship was not observed in the EHI. Overall, these results suggest that the bimanual advantage was indeed present for the strong right-handed group in both left and right hand performance, which was also observed in strong right-handed participants according to the EHI.

Table 21

Descriptive Statistics of Temporal Variability (ms.) for the Right-Handed Participants (The Handedness Inventory)

	Between Hands		Left Hand		Right Hand	
	m	*SD*	*m*	*SD*	*m*	*SD*
Bimanual In-phase	11.59	8.98	96.59	66.71	86.02	51.62
Left-Lead Out-of-Phase	41.27	15.48	109.16	55.46	75.65	29.78
Right-Lead Out-of-Phase	40.65	13.74	74.21	35.64	94.84	41.23
Unimanual			131.00	64.50	115.00	53.04

Table 22

Post Hoc (LSD) Analysis of Variability Between Experimental Conditions for Right-Handed Participants (The Handedness Inventory)

Condition		Mean Difference	Significance
Between Hands			
Bimanual In-phase	Left-Lead Out-of-Phase	29.68	0.000
Bimanual In-phase	Right-Lead Out-of-Phase	29.06	0.000
Right-Lead Out-of-Phase	Left-Lead Out-of-Phase	0.62	0.868
Right Hand			
Bimanual In-phase	Left-Lead Out-of-Phase	10.37	0.416
Bimanual In-phase	Right-Lead Out-of-Phase	8.82	0.489
Bimanual In-phase	Unimanual Right	28.98	0.025
Left-Lead Out-of-Phase	Right-Lead Out-of-Phase	19.18	0.134
Left-Lead Out-of-Phase	Unimanual Right	39.35	0.003
Right-Lead Out-of-Phase	Unimanual Right	20.17	0.116
Left Hand			
Bimanual In-phase	Left-Lead Out-of-Phase	12.57	0.437
Bimanual In-phase	Right-Lead Out-of-Phase	22.38	0.168
Bimanual In-phase	Unimanual Left	34.41	0.035
Left-Lead Out-of-Phase	Right-Lead Out-of-Phase	34.95	0.032
Left-Lead Out-of-Phase	Unimanual Left	21.84	0.178
Right-Lead Out-of-Phase	Unimanual Left	56.79	0.001

*$p<0.05$ **$p<0.01$

The means and standard deviations for the left-handed group (n=12) are presented in Table 22. For the left-handed group, one-way ANOVA results revealed significant variation between the experimental groups for between hand performance, F(2,33)=24.62, $p \leq 0.001$, as was seen with the EHI. Also, as was also seen in the EHI, one-way ANOVA results revealed no significant variation between the experimental groups for performance in the left hand (F(3,44)=0.761, $p = 0.52$) and in the right hand (F(3,44)=2.61, $p=0.06$); however, variation in the right hand approached significance. Notably, the bimanual in-phase condition was significantly less variable compared to the right-lead out-of-phase condition ($p<0.05$) and the unimanual right condition ($p<0.05$), which was not observed in the EHI. Overall, these results suggest that the bimanual advantage was present during right hand performance for the left-handed participants, but not during left hand performance. These results are partially in support of the proposed hypothesis. Inconsistent with the EHI, the bimanual advantage was not supported in the right or left hand performance.

Table 23

Descriptive Statistics of Temporal Variability (ms.) for the Left-Handed Participants (The Handedness Inventory)

	Between Hands		Left Hand		Right Hand	
	m	*SD*	*m*	*SD*	*m*	*SD*
Bimanual In-phase	10.20	4.61	73.96	35.14	65.31	23.92
Left-Lead Out-of-Phase	44.03	15.71	83.98	30.44	91.85	46.00
Right-Lead Out-of-Phase	38.84	14.74	97.60	60.27	110.36	37.79
Unimanual			78.32	29.49	110.89	65.79

Table 24

Post Hoc (LSD) Analysis of Variability between Experimental Conditions for Left-Handed Participants (The Handedness Inventory)

Condition		Mean Difference	Significance
Between Hands			
Bimanual In-phase	Left-Lead Out-of-Phase	33.83	0.000**
Bimanual In-phase	Right-Lead Out-of-Phase	28.64	0.000**
Right-Lead Out-of-Phase	Left-Lead Out-of-Phase	5.19	0.582
Right Hand			
Bimanual In-phase	Left-Lead Out-of-Phase	26.54	0.164
Bimanual In-phase	Right-Lead Out-of-Phase	45.05	0.021*
Bimanual In-phase	Unimanual Right	45.58	0.019*
Left-Lead Out-of-Phase	Right-Lead Out-of-Phase	18.51	0.329
Left-Lead Out-of-Phase	Unimanual Right	19.04	0.316
Right-Lead Out-of-Phase	Unimanual Right	0.53	0.978
Left Hand			
Bimanual In-phase	Left-Lead Out-of-Phase	10.02	0.551
Bimanual In-phase	Right-Lead Out-of-Phase	23.64	0.163
Bimanual In-phase	Unimanual Left	4.36	0.795
Left-Lead Out-of-Phase	Right-Lead Out-of-Phase	13.62	0.418
Left-Lead Out-of-Phase	Unimanual Left	5.66	0.736
Right-Lead Out-of-Phase	Unimanual Left	19.28	0.254

**p*<0.05 ***p*<0.01

Similar to the EHI, similarities were observed between the strong left-handed group and the mixed-handed group according to The Handedness Inventory. For instance, both the left- and mixed-handed groups did not display the bimanual advantage in left hand performance; however, the left-handed participants did display the bimanual advantage in the right hand performance, which was not observed in the mixed-handed group. Due to an observed similarity between the left-handed group and the mixed-handed group, these two groups were combined. Follow up analysis was conducted assessing the relationship between tapping performance and handedness, with handedness categorized into two groups: right handers and mixed/left handers.

As was seen with the EHI, a repeated measures two-way ANOVA revealed no significant interaction in performance between hands ($F_{(1.72,92.90)}=2.14$, p=0.13), in the right hand ($F_{(2.86,}$

$_{154.38)}$=1.23, p=0.30), or in the left hand ($F_{(2.66,143.73)}$=1.67, p=0.18); however, the main effect for tapping was significant for performance between hands ($F_{(1.72,92.90)}$=102.36, p≤0.001), in the right hand ($F_{(2.86,154.38)}$=9.33, p≤0.001), and in the left hand ($F_{(2.66, 143.73)}$=4.68, p≤0.001). Similar to the EHI, a follow up one-way ANOVA was conducted on the combined group of left- and mixed-handed participants.

The means and standard deviations for each experimental condition for the combined group (n=31) are presented in Table 25. For the combined group, one-way ANOVA results revealed significant variation between the experimental groups for performance between hands ($F_{(2,90)}$=39.31,p≤0.001) and in the right hand ($F_{(2,120)}$=4.29, p<0.01), which was also observed with the EHI. Post hoc comparisons for The Handedness Inventory were identical to results for the EHI, except the unimanual right condition was not significantly more variable than the left-lead out-of-phase condition in right hand performance as was seen with the EHI (See Table 26). Also, as was seen with the EHI, one-way ANOVA results for The Handedness Inventory revealed no significant variation between the experimental conditions for performance in the left hand ($F_{(3,120)}$=0.476, p=0.699). Overall, these results suggest that the bimanual advantage was present in right hand performance for the combined group, but was not present in left hand performance. These results partially support the proposed hypothesis, as the unimanual condition was not the most variable in both left and right hand performance. Also, these results were also seen in the EHI combined group of strong left- and weak-handed participants.

Table 25

Descriptive Statistics of Temporal Variability (ms.) for the Left-Handed and Mixed-Handed Participants (The Handedness Inventory)

	Between Hands		Left Hand		Right Hand	
	m	*SD*	*m*	*SD*	*m*	*SD*
Bimanual In-phase	9.54	4.39	91.25	46.00	74.18	26.05
Left-Lead Out-of-Phase	40.76	14.15	104.20	62.76	90.72	63.80
Right-Lead Out-of-Phase	42.58	24.42	93.18	59.88	115.99	54.57
Unimanual			104.30	55.65	112.33	57.80

Table 26

Post Hoc (LSD) Analysis of Variability Between Experimental Conditions for Left-Handed and Mixed-Handed Participants (The Handedness Inventory)

Condition		Mean Difference	Significance
Between Hands			
Bimanual In-phase	Left-Lead Out-of-Phase	31.22	0.000**
Bimanual In-phase	Right-Lead Out-of-Phase	33.03	0.000**
Right-Lead Out-of-Phase	Left-Lead Out-of-Phase	1.82	0.901
Right Hand			
Bimanual In-phase	Left-Lead Out-of-Phase	16.54	0.218
Bimanual In-phase	Right-Lead Out-of-Phase	41.81	0.002*
Bimanual In-phase	Unimanual Right	38.15	0.005*
Left-Lead Out-of-Phase	Right-Lead Out-of-Phase	25.27	0.061
Left-Lead Out-of-Phase	Unimanual Right	21.61	0.108
Right-Lead Out-of-Phase	Unimanual Right	3.66	0.785
Left Hand			
Bimanual In-phase	Left-Lead Out-of-Phase	12.95	0.368
Bimanual In-phase	Right-Lead Out-of-Phase	1.93	0.893
Bimanual In-phase	Unimanual Left	13.06	0.364
Left-Lead Out-of-Phase	Right-Lead Out-of-Phase	11.02	0.444
Left-Lead Out-of-Phase	Unimanual Left	0.11	0.994
Right-Lead Out-of-Phase	Unimanual Left	11.13	0.439

$^*p<0.05$ $^{**}p<0.01$

Coordination and Musical/Athletic Experience

Hypothesis 3a and 3b. It was hypothesized that participants with previous musical or athletic experience greater than one year would display less temporal variability across all experimental conditions. An independent samples t-test was conducted to compare temporal variability in the experimental tapping conditions in the athletic and no athletic groups. Independent samples t-tests revealed no significant difference between participants with and without athletic experience for temporal variability across conditions between hands (see Table 27), in the right hand (see Table 28), and in the left hand (see Table 29). These results suggest that athletic experience did not influence the participants' performance on the tapping conditions.

Table 27

t-test Results Comparing Athletic and No Athletic Experience on Temporal Variability in Tapping Between Hands

	Mean and SD by Condition			
	Athletic	No Athletic	*t*	sig
Bimanual In-phase	10.40 (7.03)	10.70 (6.30)	-0.131	0.896
Left-lead Out-of-phase	39.96 (13.96)	45.20 (17.16)	-1.067	0.291
Right-Lead Out-of-phase	39.18 (11.85)	52.08 (38.49)	-1.098	0.297

Note. Standard deviations appear in parentheses below means.

Table 28

t-test Results Comparing Athletic and No Athletic Experience on Temporal Variability in Tapping for the Right Hand

	Mean and SD by Condition			
	Athletic	No Athletic	*t*	sig
Bimanual In-phase	81.82 (42.66)	69.82 (22.16)	0.900	0.372
Left-lead Out-of-phase	79.89 (38.82)	100.76 (87.41)	-0.773	0.456
Right-Lead Out-of-phase	104.56 (43.05)	114.67 (73.40)	-0.439	0.669
Unimanual Right	109.22 (52.84)	131.13 (63.84)	-1.184	0.242

Note. Standard deviations appear in parentheses below means.

Table 29

t-test Results Comparing Athletic and No Athletic Experience on Temporal Variability in Tapping for the Left Hand

	Mean and SD by Condition			
	Athletic	No Athletic	*t*	sig
Bimanual In-phase	92.67 (54.72)	97.57 (62.23)	-0.259	0.797
Left-lead Out-of-phase	98.93 (42.22)	137.04 (100.51)	-1.232	0.244
Right-Lead Out-of-phase	86.10 (47.04)	79.03 (67.24)	0.409	0.684
Unimanual Left	111.91 (51.40)	133.85 (90.61)	-1.076	0.287

Note. Standard deviations appear in parentheses below means.

Independent samples t-test were also conducted to compare temporal variability across all experimental conditions between participants with and without musical experience. The t-test results revealed no significant difference between participants with and without musical experience for temporal variability across conditions between hands (see Table 30), in the right hand (see Table 31), and in the left hand (see Table 32). These results suggest that previous musical experience did not influence participants' performance on the tapping conditions.

Table 30

t-test Results Comparing Musical and No Musical Experience on Temporal Variability in Tapping Between Hands

	Mean and SD by Condition			
	Music	No Music	*t*	sig
Bimanual In-phase	10.57 (7.85)	10.29 (5.06)	0.147	0.884
Left-lead Out-of-phase	39.69 (14.14)	43.00 (15.46)	-0.822	0.415
Right-Lead Out-of-phase	42.58 (13.85)	40.38 (27.67)	0.395	0.694

Note. Standard deviations appear in parentheses below means.

Table 31

t-test Results Comparing Participants Musical and No Musical Experience on Temporal Variability in Tapping for the Right Hand

	Mean and SD by Condition			
	Music	No Music	*t*	Sig
Bimanual In-phase	82.49 (43.48)	74.55 (33.14)	0.707	0.483
Left-lead Out-of-phase	75.55 (36.34)	97.04 (67.90)	-1.540	0.129
Right-Lead Out-of-phase	106.71 (47.11)	106.29 (54.81)	0.030	0.976
Unimanual Right	111.49 (46.93)	116.66 (67.19)	-0.339	0.736

Note. Standard deviations appear in parentheses below means.

Table 32

t-test Results Comparing Musical and No Musical Experience on Temporal Variability in Tapping for the Left Hand

	Mean and SD by Condition			
	Music	No Music	*t*	sig
Bimanual In-phase	99.20 (64.61)	85.03 (37.97)	0.928	0.357
Left-lead Out-of-phase	110.94 (54.71)	99.41 (66.10)	0.710	0.481
Right-Lead Out-of-phase	83.65 (40.53)	86.35 (65.00)	-0.192	0.849
Unimanual Left	121.60 (61.50)	107.92 (59.88)	0.821	0.415

Note. Standard deviations appear in parentheses below means.

Discussion

The present study sought out to further understand the relationship between hand dominance and bimanual motor coordination in a young adult community sample. As previously hypothesized, the synchronized, in-phase coordination of two hands results in less temporal variability when tapping compared to unimanual tapping, which has been referred to as a bimanual advantage (Helmuth & Ivry, 1996). Also, hand dominance has been shown to have varying effects on bimanual performance (Fagard & Corroyer, 2012; Kourtis et al., 2014; Ponton, 1987). However, studies examining this relationship are limited. The present study aimed at expanding upon the existing body of literature examining the existence of a bimanual advantage and potential factors influencing bimanual coordination, including hand dominance and musical/athletic experience.

Hypothesis 1a

It was hypothesized that individuals would perform with less efficiency, or greater temporal variability, on the unimanual tapping conditions compared to the bimanual in-phase condition, which would further support the presence of a bimanual advantage. Data from the present study supported this hypothesis as evidenced by significantly greater temporal variability in the unimanual conditions compared to the bimanual in-phase conditions for both right and left hand performance. These results are consistent with previous findings suggesting the presence of a bimanual advantage (Helmuth & Ivry, 1996). Moreover, this evidence suggests that using two fingers, or effectors, results in greater efficiency compared to tapping with one finger.

Hypothesis 1b

In regard to out-of-phase performance, it was hypothesized that the out-of-phase conditions would result in the greatest amount of variability compared to the unimanual and *bimanual in-phase conditions.* In the present study, mixed findings were found for this hypothesis. For between hands performance, the results were consistent with previous findings (Bangert et al., 2010) and the proposed hypothesis, such that both the right-lead out-of-phase and left-lead out-of-phase conditions were significantly more variable compared to the bimanual in-phase condition. Moreover, consistency in performance between hands was more variable when a more complex phase pattern was incorporated.

Within right and left hand performance, the findings of the present study were inconsistent and did not clearly mirror previous findings (Serrien, 2008). For instance, the right-lead out-of-phase condition performed significantly more variably compared to the bimanual in-phase condition, as expected; however, there were no other significant differences between the conditions as predicted. Additionally, within left hand performance, there was only one significant relationship in the out-of-phase conditions with significantly more variability in the right-lead out-of-phase condition compared to the unimanual left condition. Despite these two significant relationships, it appears that the proposed hypothesis was not consistently supported in right and left hand performance.

The inconsistent findings in the present study may be attributed to the difference in experimental methods between the present study and previous research. For instance, participants in Serrien’s (2008) study completed two finger combinations for each experimental condition, whereas the present study asked participants to use one finger from each hand. Additionally, Serrien’s (2008) study measured temporal accuracy, while the present study measured temporal consistency. Also, the previous study conducted by Serrien (2008) was not interested in the relationship between hand dominance and bimanual coordination; therefore, only right-handed participants were incorporated in the study. The fact that the present study included a heterogeneous sample based on hand dominance may have contributed to the non-significant findings (see discussion for hypothesis 2).

Additionally, the lack of significant findings in the present study may be indicative of the fact that there is no real significant difference in tapping variability between the out-of-phase condition with either the bimanual in-phase or unimanual conditions. The bimanual advantage appears to be present (i.e., significant difference between the unimanual and bimanual in-phase conditions); however, it is possible that the out-of-phase condition is truly not significantly different from the other tapping conditions. Moreover, the present study demonstrated that out-of-phase tapping resulted in the greatest amount of variability when considering between hands performance, but this relationship was not consistently demonstrated when assessing performance independently in either the right or left hand. This finding is slightly surprising because it has been consistently demonstrated in previous studies that out-of-phase bimanual tapping results in greater variability compared to less complex patterns of tapping, such as bimanual in-phase and unimanual tapping (Bangert et al., 2010; Serrien, 2008).

Hypothesis 2

It was predicted that temporal variability across the experiential conditions would be significantly related to hand dominance. The original regression analysis in the present study assessing handedness as a continuous variable revealed no significant differences between hand dominance, as reported by the EHI and The Handedness Inventory, and tapping variability across the experimental conditions. As suggested by Annett (1976), handedness should not be categorized as a dichotomous variable, but rather as subgroups across a distribution. Therefore, follow-up analyses were conducted to assess the relationship between temporal variability and hand dominance as a categorical variable with subgroups across the distribution of handedness.

Hypothesis 2a. *It was hypothesized that individuals with strong hand dominance would perform with greater efficiency (i.e., less variability) on the unimanual and out-of-phase conditions and more variability on the bimanual in-phase condition (i.e., limited bimanual advantage) compared to those with weak hand dominance.* The results of the present study revealed that participants with strong hand dominance performed more variably on the out-of-phase conditions compared to the bimanual in-phase condition when considering between hands performance. Additionally, participants with strong hand dominance performed more variably on the unimanual condition compared to the bimanual in-phase condition when considering performance in both the left and right hands. Notably, this difference was only significant in the right hand for The Handedness Inventory. Altogether, these results do not support the proposed hypothesis and are inconsistent with some of the findings in the neuroscience literature. It has been reported that individuals with weak hand dominance have smaller corpus callosums (Luders et al., 2010), and small callosal size has been shown to be related to poor performance on out-of-phase conditions (Flint et al., 2011a). Thus, individuals with strong hand dominance should show better performance in the out-of-phase and unimanual conditions. However, the current results showed the opposite pattern: stronger laterality is actually associated with poorer performance on unimanual and out-of-phase bimanual tasks. It appears that the bimanual advantage is significantly present within strong-handed individuals.

It is interesting that some of the findings in the previous behavior studies were actually consistent with the current finding. It has been found that participants with strong hand dominance performed more variably on unimanual tasks (Ponton, 1987) and complex out-of-phase tasks (Kourtis et al., 2014) compared to those with inconsistent or weak hand dominance. The discrepancy between these studies and the findings from the previous neuroscience literature may be related to measures of the corpus callosum. It has been shown that larger corpus callosums correlate with more variability in performance on motor tasks requiring more interhemispheric communication, such as the out-of-phase bimanual and unimanual tasks (Flint et al., 2011a) and that individuals with strong hand dominance have larger corpus callosums (Luders et al., 2010). The present study, as well as those behavioral studies, did not incorporate neuroimaging to assess callosal size; therefore, it is possible that callosal size did not significantly differ between the strong- and weak-handed participants in the present study. Moreover, a lack of difference between callosal size may explain why the results of the present study did not support the proposed hypothesis. Additionally, Fling and colleagues (2011a) study only included strongly right-handed participants. Thus, it is possible that the relationship between callosal size and performance on motor tasks requiring more interhemispheric communication would differ for strong left handers, which were included in the present study.

Hypothesis 2b. *Alternatively, it was proposed that weak-handed participants would perform with greater variability on the unimanual and out-of-phase conditions displaying a bimanual advantage.* Results of the present study partially supported the proposed hypothesis in regards to predictions of out-of-phase performance as weak handed participants had significantly greater variability on the out-of-phase conditions compared to the bimanual in-phase condition in regards to between hands performance. In contrast, there was no significant difference between the out-of-phase and in-phase conditions within right or left hand performance for the weak-handed participants as reported by the EHI. Analysis using the Handedness Inventory revealed one significant relationship with performance in the right-lead out-of-phase condition being significantly more variable compared to the bimanual in-phase condition within right hand performance. Overall, the results partially support the proposed hypothesis in regards to weak-handed participants and out-of-phase performance (i.e., out-of-phase performance more variable than bimanual in-phase in between hands comparison); however, this pattern was not consistent across the results, including performance in the left and right hand.

Lack of significant difference between the unimanual conditions and the bimanual in-phase condition (either left or right hand performance using both the EHI and The Handedness Inventory) indicated that the bimanual advantage was not necessarily present for the weak-handed participants. This is an interesting result because Luders and colleagues (2010) have suggested that out-of-phase and unimanual bimanual coordination required high demands of interhemispheric communication compared to the in-phase bimanual movements. The poor performance in these two types of tasks was partially due to the small callosal size in the weak handers. The current data suggest that the demands of interhemipheric communication for out-of-phase bimanual coordination may be even higher than that for the unimanual movements. Therefore, differences between the unimanual and the bimanual in-phase condition, or a bimanual advantage, were not observed, but the results of the present study did reveal a significant difference between the bimanual out-of-phase and in-phase conditions.

There are a few possible explanations for why the bimanual advantage was not clearly observed in the weak-handed group. For instance, researchers have displayed that individuals with weak hand dominance perform equally fast on both asymmetrical and symmetrical tasks, whereas strong-handed individuals display differences in performance across conditions (Kourtis et al., 2014). Although this study did not assess unimanual performance, these results may explain the results of the present study. Therefore, it may be possible that equal lateralization across hemispheres may be advantageous when completing motor tasks, resulting in a truly insignificant difference in performance between tapping conditions. However, in the present, the advantage of equal lateralization, or weak handedness, does not result in a bimanual advantage and, instead, suggests bimanual in-phase performance results in less variability than unimanual performance.

Another possible explanation, as previously mentioned, is that experimental factors (i.e., sampling, experimental paradigm) may account for the non-significant finding. For instance, the proposed hypothesis was dependent upon research findings of callosal size (Flint et al., 2011a), which only assessed performance and corpos callosum sizes in individuals with strong right hand dominance. Therefore, it is possible that the results would have differed if weak-handed and left-handed participants were assessed. Also, it is possible that strong-handed and weak-handed participants had similar corpus callosum sizes, which was not assessed in the study.

Follow up analysis in the present study revealed unique characteristics and similarities across the strong- and weak-handedness groups. Evaluation of the strong right-handed participants revealed the presence of a bimanual advantage, as was seen in the analysis of the strong-handed participants. In contrast, the strong left-handed participants displayed a different pattern of performance. The strong left-handed participants performed similar to the weak-handed participants in that they did not display a bimanual advantage or significant differences across performance in either the right or left hand. Furthermore, the combined group of strong left-handed and weak-handed participants revealed that the bimanual advantage was present for performance in the right hand, but was not present in left hand performance. Overall, these results suggest that strong left hemisphere lateralization results in a more pronounced bimanual advantage compared to those with strong right hemisphere or weak lateralization.

Hypothesis 3

It was hypothesized that participants with reported musical and athletic experience greater than one year would perform less variably on all experimental tapping conditions compared to those with no musical or athletic experience. Results from the present study were inconsistent with the proposed hypothesis. Moreover, participants with musical and athletic experience did not perform significantly more or less variable compared to those without previous musical and athletic experience.

The non-significant findings in the present study may be attributable to several experimental factors. For instance, participants were asked to indicate whether they had musical or athletic experience beyond one year in the form of a yes or no question. Additionally, some participants reported more specific details regarding their experience, such as type of instrument or sport, length of experience, and age at onset of training. However, the questions on the demographic questionnaire did not specifically prompt participants to provide more detailed information regarding their experience; therefore, this information was not available for all participants. Previous research suggests that neural correlates may differ not only between musicians and non-musicians but also by the individual's specific training, such as conductor or pianist (Munte et al., 2003). Additionally, previous research suggests practicing musical instruments increase white matter plasticity, specifically when training began earlier in life (Bengtsson et al., 2005). Moreover, these factors may account for variability observed between musicians or athletes and those with no experience.

Additionally, to knowledge, assessment of bimanual motor performance in musicians and athletes has not been previously studied. Therefore, the present hypothesis may be a novel experimental question. The current data did not support that the musical or athletic training could significantly impact the bimanual coordination. However, future studies are needed to justify the current findings. Previous studies have suggested that differences in neural activity between novice and expert athletes diminish when participants completed novel motor tasks (Haufler et al., 2000). Thus, it is also possible that the present study resulted in insignificant findings due to the fact that participants completed a novel task, tapping, instead of a task consistent with their previous experience, such as playing a musical instrument or completing an athletic routine.

Limitations

Several limitations are evident in the present study. A primary limitation of the present study was that the distribution of the sample included an unbalanced representation across the continuum of handedness. Unfortunately, an equal distribution of weak and strong right- and left-handed individuals does not exist in the general population; therefore, sampling across the continuum of handedness can be challenging (Kourtis et al., 2014). In the current study, more efforts were put forward towards recruiting left handers in order to maximize the possibility of covering a reasonable range of the handedness continuum. As a result, the percentage of the left handers in the present study (see Table 1) is much higher than that in the population (~10%).

Another potential limitation of the present study was the tapping paradigm used to measure bimanual coordination. Tapping has been consistently shown to be an efficient measure of bimanual coordination as it utilizes minimal activation of muscles and allows researchers to easily assess different degrees of interhemispheric interaction by using varying phase patterns (Fling et al., 2011a). However, there are a variety of formats of tapping, which include minor differences in the requested actions (i.e., cued tapping or repetitive tapping), cues (i.e., visual or auditory), complexity of coordinated phases (i.e., lag time in out-of-phase conditions), and digital involvement (i.e., bidigital or unidigital). Therefore, the discrepancy of the current results with previous literature needs to be interpreted with caution. The inability to collect neuroimaging data limits further interpretation of some of the conflicting results.

In addition, there were several notable weaknesses regarding the examination of musical and athletic experience. As previously mentioned, the limited format for assessing musical and athletic experience may have affected the findings of the present study. Moreover, the present study did not thoroughly evaluate the musical and athletic performance of participants by asking questions regarding length, onset, and type of experience. Nonetheless, assessing the relationship between musical and athletic experience on bimanual coordination appears to be a novel question. Despite the lack of significant findings, the present study was an initial attempt at understanding this relationship and resulted in innovative ideas for future research in this area, which will be further discussed in the following section.

Future Directions

Even though the present study generally supported the presence of a bimanual advantage in a tapping paradigm, there are several empirical questions that can be further assessed in future research. For instance, the present study revealed that performance in coordinated conditions significantly varies for individuals with strong, or consistent, hand dominance; however, a similar pattern was not observed in individuals with weak handedness. Moreover, it appears that individuals with strong left-handedness behave similar to those with weak handedness. It is important for future research to continue to assess the patterns of performance on coordinated tasks across the entire continuum of handedness. Additionally, the underlying processes of these patterns of behavior also need to be further assessed. Neuroimaging may be a vital instrument in gaining a more in-depth understanding of the processes underlying handedness consistency and bimanual coordination.

In addition, the present study did not find significant differences in tapping variability between those with musical or athletic experience and those with no previous experience; however, future research may incorporate alternative methods and samples to further understand this relationship. For instance, a more thorough assessment of musical and athletic experience could allow researchers to more accurately distinguish potential differences in performance. Moreover, participants could be prompted to provide information regarding the type, length, and onset of their experience. Even further, future researchers may also be interested in assessing baseline bimanual coordination performance before participants participate in music or athletic training. This would allow researchers to further understand whether musical or athletic experience enhances bimanual coordination in everyday tasks or that efficient bimanual coordination is an innate characteristic.

Additionally, future research assessing bimanual coordination may be beneficial to further understanding various clinical populations. For instance, as previously mentioned, motor deficits are commonly observed in neurodevelopmental disorders, such as developmental coordination disorder and autism spectrum disorder (APA, 2013). Additionally, it has been shown that performance on bimanual tasks can be diagnostically useful in psychiatric populations (Gorynia et al., 2003). Overall, a more in depth understanding of bimanual coordination in relation to hand dominance and the underlying processes of coordination may enhance the conceptualization and treatment of various psychological disorders with motor impairments.

Conclusion

The present study used a tapping paradigm to examine bimanual coordination and a potential bimanual advantage. Also, this study examined the effects of hand dominance and musical/athletic experience on coordination. Across the entire sample, the bimanual advantage was evident; however, the out-of-phase conditions were not significantly more variable as predicted. Despite overall evidence of the bimanual advantage, this pattern was not consistently displayed across the handedness continuum. Moreover, strong-handed participants displayed a strong bimanual advantage, whereas weak-handed participants displayed a weak or absent bimanual advantage. Several other studies have found varying performance in bimanual coordination across the continuum of hand dominance; however, the present study expands upon the existing literature and understanding of this relationship. Additionally, no significant differences were observed between those with and without musical/athletic experience. In the future, studies assessing coordination using a tapping paradigm should also incorporate neuroimaging methods to further understand the underlying processes of bimanual coordination and the effects of handedness on coordination. Relevant studies are needed as they will contribute to further understanding motor deficits commonly observed in a wide range of clinical populations. Overall, the results of the present study will be relevant for future studies concerned with bimanual coordination and the underlying processes of motor movement.

References

Annett, M. (1970). A classification of hand preference by association analysis. *British Journal of Psychology, 61*(3), 303-321.

Annett, M. (1976). A coordination of hand preference and skill replicated. *British Journal of Psychology, 67*(4), 587-592.

APA. (2013). *DSM-5. Diagnostic and statistical manual of mental disorders* (5th edition). Washington, DC: American Psychiatric Publishing.

Bangert, A. S., Reuter-Lorenz, P. A., Walsh, C. M., Schachter, A. B., & Seidler, R. D. (2010). Bimanual coordination and aging: Neurobehavioral implications. *Neropsychologia, 48*(4), 1165-1170.

Barber, A. D., Srinivasan, P., Joel, S. E., Caffo, B. S., Pekar, J. J., & Mostofsky, S. H. (2012). Motor "dexterity"?: Evidence that left hemisphere lateralization of motor circuit connectivity is associated with better motor performance in children. *Cerebral Cortex, 22*(1), 51-59.

Bengtsson, S. L., Nagy, Z., Skare, S., Forsman, L., Forssberg, H., & Ullen, F. (2005). Extensive piano practing has regionally specific effects on white matter development. *Nature Neuroscience, 8*(9), 1148-1150.

Bernard, J. A. & Seidler, R. D. (2012). Hand dominance and age have interactive effects on motor cortical representations. PLoS ONE 7(9): e45443, 1-11.

Bernard, J. A., Taylor, S. F., & Seidler, R. D. (2011). Handedness, dexterity, and motor cortical representations. *Journal of Neurophysiology, 105*, 88-99.

Bo, J. Bastian, A. J., Kagerer, F. A., Contreras-Vidal, J. L., & Clark, J. E. (2008). Temporal variability in continuous versus discontinuous drawing for children with developmental coordination disorder. *Neuroscience Letters, 431*(3), 215-220.

Briggs, G. G. & Nebes, R. D. (1975). Patterns of hand preference in a student population. *Cortex, 11*(3), 230-238.

Brown, R. G., Jahanshahi, M., & Marsden, C. D. (1993). The execution of bimanual movements in patients with Parkinson's, Huntington's, and cerebellar disease. *Journal of Neurology, Neurosurgery, & Psychiatry, 56*, 295-297.

Chen, J. T., Lin, Y. Y., Shan, D. E., Wu, Z. A., Hallett, M., & Liao, K. K. (2005). Effect of transcranial magnetic stimulation on bimanual movements. *Journal of Neurophysiology, 93*, 53-63.

Corey, D. M., Hurley, M. M., & Foundas, A. L. (2001). Right and left handedness defined: A multivariate approach using hand preference and hand performance measures. *Neuropsychiatry, Neuropsychology, & Behavioral Neurology, 14*(3), 144-152.

Debaere, F., Wenderoth, N., Sunaert, S., Van Hecke, P., & Swinnen, S. P. (2004). Cerebellar and premotor function in bimanual coordination: Parametric neural responses to spatiotemporal complexity and cycling frequency. *NeuroImage, 21*, 1416-1427.

Drewing, K. & Aschersleben, G. (2003). Reduced timing variability during bimanual coupling: A role for sensory information. *The Quarterly Journal of Experimental Psychology Section A: Human Experimental Psychology, 56*(2), 329-350.

Drewing, K., Hennings, M., & Aschersleben, G. (2002). The contribution of tactile reafference to temporal regularity during bimanual finger tapping. *Psychological Research, 66*, 60-70.

Duque, J., Mazzocchio, R., Dambrosia, J., Murase, N., Olivier, E., & Cohen, L. G. (2005). Kinematically specific interhemispheric inhibition operating in the process of generation of a voluntary movement. *Cerbral Cortex, 15,* 588-593.

Fagard, J. & Hardy-leger, I. (2001). Changes in interhemispheric transfer rate and the development of bimanual coordination during childhood. *Journal of Experimental Child Psychology, 80*, 1-22.

Fagard, J. & Corroyer, D. (2002). Using a continuous index of laterality to determine how laterality is related to inhermispheric transfer and bimanual coordination in children. *Developmental Psychobiology, 43*(1), 44-56.

Fling, B. W., Chapekis, M., Reuter-Lorenz, P. A., Anguera, J., Bo, J., Langan, J., Welsh, R. C., & Seidler, R. D. (2011a). Age differences in callosal contributions to cognitive processes. *Neuropsychologia, 49*(9), 2564-2569.

Fling, B. W., Walsh, C. M., Bangert, A. S., Reuter-Lorenz, P. A., Welsh, R. C., & Seidler, R. D. (2011b). Differential callosal contributions to bimanual control in young and older adults. *Journal of Cognitive Neuroscience, 23*(9), 1-25.

Fling, B. W., Benson, B. L., & Sadler, R. D. (2013). Transcallosal sensorimotor fiber tract structure-function relationships. *Human Brain Mapping, 34*(2), 384-395.

Franz, E. A., Eliassen, J. C., Ivry, R. B., & Gazzaniga, M. S. (1996). Dissociation of spatial and temporal coupling in the bimanual movements of callosotomy patients. *Psychological Science, 7*(5),306-310.

Gbedd, J. N., Blumenthal, J., Jeffries, N. O., Rajapakse, J. C., Vaituzis, A. C., Liu, H., Berry, Y. C., Tobin, M., Nelson, J., & Castellanos, F. X. (1999). Development of the human corpus callosum during childhood and adolescence: A longitudinal MRI study. *Progress in Neuro-Psychopharmacology and Biological Psychiatry, 23*(4), 571-588.

Geffen, G. M., Jones, D. L., & Geffen, L. B. (1994). Interhemispheric control of manual motor activity. *Behavioural Brain Research, 64*(1), 131-140.

Gerloff, C. & Andres, F. G. (2002). Bimanual coordination and interhemispheric interaction. *Acta Psychologica, 110*, 161-186.

Gorynia, I., Campman, V., & Uebelhack, R. (2003). Intermanual coordination in relation to different clinical subgroups in right-handed patients with schizophrenic and other psychotic disorders. *European Archives of Psychiatry and Clinical Neuroscience, 253*, 53-59.

Gorynia, I., Dudeck, U., & Neumarker, K-J. (1994). Instability in functional motor laterality of children and adolescents with endogenous psychosis and predominantly motor disturbances. *European Archives of Psychiatry and Clinical Neuroscience, 244*, 33-38.

Gorynia, I. & Egenter, D. (2000). Intermanual coordination in relation to handedness, familial sinistrality, and lateral preferences. *Cortex, 36*, 1-18. *Neuropsychologia, 49*(9), 2564-2569.

Gorynia, I. & Schwaiger, M. (2011). Effects of handedness (left vs right) and cannabis abuse on intermanual coordination and negative outcomes in schizophrenic patients of the paranoid type. *Laterality, 16*(5), 537-558.

Habib, M., Gayraud, D., Oliva, A., Salamon, G., & Khalil, R. (1991). Effects of handedness and sex on the morphology of the corpus callosum: A study with brain magnetic resonance imaging. *Brain and Cognition, 16*(1), 41-61.

Hatfield, B. D., Haufler, A. J., Hung, T-M., & Spalding, T. W. (2004). Electroencephalographic studies of skilled psychomotor performance. *Journal of Clinical Neurophysiology, 21*(3), 144-156.

Haufler, A. J., Spalding, T. W., Santa Maria, D. L., & Hatfield, B. D. (2000). Neuro-cognitive activity during a self-paced visuospatial task: Comparative EEG profiles in marksmen and

novice shooters. *Biological Psychology, 53*, 131-160.

Heitger, M. H., Mace, M. J. M., Jastorff, J., Swinnen, S. P., & Orban, G. A. (2012). Cortical regions involved in the observation of bimanual actions. *Journal of Neurophysiology, 108*, 2594-2611.

Helmuth, L. L. & Ivry, R. B. (1996). When two hands are better than one: Reduced timing variability during bimanual movements. *Journal of Experimental Psychology: Human Perception and Performance, 22*(2), 278-293.

Huh, J., Williams, H. G., & Burke, J. R. (1998). Development of bilateral motor control in children with developmental coordination disorder. *Developmental Medicine & Child Neurology, 40*, 474-485.

Institutional Research and Information Management at Eastern Michigan University. (2013). Budget and performance transparency teporting: EMU dashboard. [Data File]. Retrieved from http://irim.emich.edu/dashboard/kpiscorecard.php

Ivry, R. B. & Hazeltine, R. E. (1995). Perception and production of temporal intervals across a range of durations-evidence for a common timing mechanism. *Journal of Experimental Psychology: Human Perception and Performance, 21,* 3-18.

Ivry, R. B. & Hazeltine, E. (1999). Subcortical locus of temporal coupling in the bimanual movements of a callosotomy patient. *Human Movement Science, 18*, 345-375.

Jancke, L., Shah, N. J., & Peters, M. (2000). Cortical activations in primary and secondary motor areas for complex bimanual movements in professional pianists. *Cognitive Brain Research, 10*, 177-183.

Johnson, K. A., Bennett, J. E., Georgiou, N., Bradshaw, J. L., Chiu, E., Cunnington, R., & Iansek, R. (2000). Bimanual co-ordination in Huntington's disease. *Experimental Brain Research, 134*, 483-489.

Kelso, J. A. S. (1984). Phase transitions and critical behavior in human bimanual coordination. *American Journal of Physiology: Regulatory, Integrative, and Comparative, 246*, R1000-R1004.

Kim, J., Lee, H. M., Kim, W. J., Park, H. J., Kim, S. W., Moon, D. H., Woo, M., & Tennant, L. K. (2008). Neural correlates of pre-performance routines in expert and novice archers. *Neuroscience Letters, 445*, 236-241.

Kirby, A. & Sugden, D. A. (2007). Children with developmental coordination disorders. *Journal of the Royal Society of Medicine, 100*, 182-186.

Koeneke, S., Lutz, K., Wustenberg, T., & Jancke, L. (2004). Bimanual versus unimanual coordination: What makes the difference. *NeuroImage, 22*, 1336-1350.

Kourtis, D., De Saedeleer, L., and Vingerhoets, G. (2014). Handedness consistency influences bimanual coordination: A behavioural and electrophysiological investigation. *Neuropsychologia, 58,* 81-87.

Lay, B. S., Sparrow, W. A., Hughes, K. M., & O'Dwyer, N. J. (2002). Practice effects on coordination and control, metabolic energy expenditure, and muscle activation. *Human Movement Science, 21*, 807-830.

Lee, D. J., Chen, Y., & Schlaug, G. (2003). Corpus callosum: Musician and gender effects. *NeuroReport, 14*(2), 205-209.

Luders, E., Cherbuin, N., Thompson, P. M., Gutman, B., Anstey, K. J., Sachdev, P., & Toga, A. W. (2010). When more is less: associations between corpus callosum size and handedness lateralization. *Neuroimage, 52*(1), 43-49.

Meyer, B. U., Roricht, S., von Einsidel, G., Kruggel, F., & Weindl, A. (1995). Inhibitory and excitatory interhemispheric transfers between motor cortical areas in normal humans and patients with abnormalities of the corpus callosum. *Brain, 118*(2), 429-440.

Milton, J., Solodkin, A., Hlustik, P., & Small, S. L. (2007). The mind of expert motor performance is cool and focused. *NeuroImage, 35*, 804-813.

Munte, T. F., Altenmuller, E., & Jancke, L. (2002). The musician's brain as a model of neuroplasticity. *Nature Reviews: Neuroscience, 3*, 473-478.

Munte, T. F., Nager, W., Beiss, T., Schroeder, C., & Altenmuller, E. (2003). Specialization the specialized: Electrophysiological investigations in professional musicians. *Annals of the New York Academy of Sciences, 999,* 131-139.

Oldfield, R. C. (1971). The assessment and analysis of handedness: The Edinburgh inventory. *Neuropsychologia, 9*(1), 97-113.

Oswald, K., Colbert, A., Bellono, R., & Bo, J. (2014, April). The effects of handedness on unimanual and bimnual tapping. Poster session presented at the 21st annual meeting of the Cognitive Neuroscience Society, Boston, MA.

Paus, T., Zijdenbos, A., Worsley, K., Collins, D. L., Blumenthal, J., Giedd, J. N., Rapoport, J. L., & Evans, A. C. (1999). Structural maturation of neural pathways in children and adolescents: in vivo study. *Science, 283*, 1908-1911.

Peters, M. & Durding, B. M. (1978). Handedness measured by finger tapping: A continuous variable. *Canadian Journal of Psychology/Revue canadienne de Psychologie, 32*(4), 257-261.

Pollok, B., Butz, M., Gross, J., & Schnitzler, A. (2007). Intercerebellar coupling contributes to bimanual coordination. *Journal of Cognitive Neuroscience, 19*(4), 704-719.

Ponton, C. W. (1987). Enhanced articulatory speed in ambidexters. *Neuropsychologia, 25*(1), 305-311.

Pujol, J., Vendrell, P., Junque, C., Marti-Vilalta, J. L., & Capdevila, A. (1993). When does human brain development end? Evidence of corpus callosum growth up to adulthood. *Annals of Neurology, 34*(1), 71-75.

Repp, B. H. (2005). Sensorimotor synchronization: A review of the tapping literature. *Psychonomic Bulletin & Review, 12*(6), 969-992.

Ross, J. S., Tkach, J., Ruggieri, P. M., Lieber, M., & Lapresto, E. (2003). The mind's eye: Functional MR imaging evaluation of golf motor imagery. *American Journal of Neuroradiology, 24*, 1036-1044.

Sadato, N., Yonekura, Y., Waki, A., Yamada, H., & Ishii, Y. (1997). Role of the supplementary motor area and the right premotor cortex in the coordination of bimanual finger movements. *The Journal of Neuroscience, 17*(24), 9667-9674.

Schlaug, G. (2001). The brain of musicians: A model for functional and structural adaptation. *Annals of the New York Academy of Sciences, 930*, 281-299.

Schlaug, G., Jancke, L., Huang, Y., Staiger, J. F., & Steinmetz, H. (1995). Increased corpus callosum size in musicians. *Neuropsychologia, 33*(8), 1047-1055.

Semjen, A. & Ivry, R. B. (2001). The couple oscillator model of between-hand coordination in alternate-hand tapping: A reappraisal. *A Journal of Experimental Psychology: Human Perception and Performance, 27*(2), 251-265.

Serrien, D. J. (2008). Coordination constraints during bimanual versus unimanual performance conditions. *Neuropsychologia, 46*, 419-425.

Serrien, D. J. & Wiesendanger, M. (2000). Temporal control of bimanual task in patients with cerebellar dysfunction. *Neuropsychologia, 38*, 558-565.

Sohn, Y. H., Jung, H. Y., & Kaelin-Lang, A. (2003). Excitability of the ipsilateral motor cortex during phasic voluntary hand movement. *Experimental Brain Research, 148*, 176-185.

Stinear, J. W. & Byblow, W. D. (2002). Disinhibition in the human motor cortex is enhanced by synchronous upper limb movements. *Journal of Physiology, 543*(1), 307-316

Studenka, B. E., Eliasz, K. L., Shore, D. I., & Balasubramaniam, R. (2014). Crossing the arms confuses the clocks: Sensory feedback and the bimanual advantage. *Psychonomic Bulletin & Review, 21*(2), 390-397.

Swinnen, S. P. (2002). Intermanual coordination: From behavioural principles to neural-network interactions. *Nature Reviews Neuroscience, 3*, 348-359.

Swinnen, S. P., Jardin, K., Meulenbroek, R., Dounskaia, N., & Hofkens-Van Den Brandt, M. (1997). Egocentric and allocentric constraints in the expression of patterns of interlimb coordination. *Journal of Cognitive Neuroscience, 9*(3),348-377.

Swinnen, S. P. & Wenderoth, N. (2004). Two hands, one brain: Cognitive neuroscience of bimanual skill. *Trends in Cognitive Science, 8*(1), 18-25.

Tabares-Seisdedos, R., Salazar-Fraile, J., Selva-Vera, G., Balanza-Martinez, V., Ballester-Sanchez, F., Cozar-Santiago, R., Leal-Cercos, C., & Gomez-Beneyto, M. (2003). Abnormal motor asymmetry only during bimanual movement in schizophrenic patients compared with healthy subjects. *Schizophrenia Research, 61*, 245-253.

Tinazzi, M. & Zanette, G. (1998). Modulation of ipsilateral motor cortex in man during unimanual finger movements of different complexities. *Neuroscience Letters, 244*, 121-124.

Ullen, F., Forssberg, H., & Ehrsson, H. H. (2003). Neural networks for the coordination of hands in time. *Journal of Neurophysiology, 89*, 1126-1135.

Vercauteren, K., Pleysier, T., Van Belle, L., Swinnen, S. P., & Wenderoth, N. (2008). Unimanual muscle activation increases interhemispheric inhibition from the active to the resting hemisphere. *Neuroscience Letters, 445*, 209-213.

Volman, M. J., Laroy, M. E., & Jongmans, M. J. (2006). Rhythmic coordination of hand and foot in children with Developmental Coordination Disorder. *Child Care Health Dev., 32*, 693-702.

Williams, S. M. (1991). Handedness inventories: Edinburgh versus Annett. *Neuropsychology, 5*(1), 43-48.

Wing, A. M. & Kristofferson, A. B. (1973a). Response delays and the timing of discrete motor responses. *Perception & Psychophysics, 14*(1), 5-12.

Wing, A. M. & Kristofferson, A. B. (1973b). The timing of interreponsive intervals. *Perception & Psychophysics, 13*(3), 455-460.

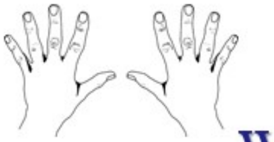
Witelson, S. F. (1985). The brain connection: The corpus callosum is larger in left-handers. *Science, 229*, 665-668.

Witelson, S. F. (1989). Hand and sex differences in the isthmus and genu of the human corpus callosum: A postmortem morphological study. *Brain, 112*(3), 799-835.

APPENDICES

APPENDIX A

Recruitment Flier



WOULD YOU LIKE TO MAKE A CONTRIBUTION TO SCIENCE?

We are looking for volunteers to participate in visuomotor coordination research.

We are studying the effects of hand dominance in hand coordination tasks.
The testing will last about *30 minutes*.
You can receive *class credit* for your participation.

We are looking for normal, healthy men and women who are older than 18 with normal or corrected vision.

If you are interested in participating or would like more information concerning this study, please email Kaitlin Oswald at koswald1@emich.edu

Motor coordination
Kaitlin Oswald
koswald1@emich.edu

Motor coordination
Kaitlin Oswald
koswald1@emich.edu

Motor coordination
Kaitlin Oswald
koswald1@emich.edu

Motor coordination
Kaitlin Oswald
koswald1@emich.edu

Motor coordination
Kaitlin Oswald
koswald1@emich.edu

Motor coordination
Kaitlin Oswald
koswald1@emich.edu

Motor coordination
Kaitlin Oswald
koswald1@emich.edu

Motor coordination
Kaitlin Oswald
koswald1@emich.edu

Motor coordination
Kaitlin Oswald
koswald1@emich.edu

Motor coordination
Kaitlin Oswald
koswald1@emich.edu

APPENDIX B

Informed Consent

Project Title: The Effects of Handedness on Bimanual Motor Coordination

Investigator: Kaitlin Oswald, Graduate Student, Department of Psychology, Eastern Michigan University

Purpose of the Study: The overall objective of this study is to gain a better understanding of motor behavior in individuals with varying consistencies in hand preference. This proposal will investigate the mechanism that underlies motor coordination and the role hand dominance plays in coordinated tasks in adults. This work will advance our understanding of motor control and brain/behavior relationships.

Procedure: A research assistant will explain the study to you, answer any questions you may have, and witness your signature to this consent form.

You have been invited to participate in this study because you are at least 18 years old. No gender, ethnic or racial backgrounds will be excluded from this research. Participants will be excluded if they have any medical or mental conditions, such as head injuries, Attention-Deficit Hyperactivity Disorder, Learning Disability, Developmental Coordination Disorder, or Autism Spectrum Disorder.

You will first be asked to complete a questionnaire about your demographic information and general health history. Sample questions include, history of a head injury or bone fractures, and years of experience playing a musical instrument. Additionally, you will complete two brief questionnaires assessing your hand preference in various daily tasks, such as writing or opening a box. These questions and assessments will help us determine whether participants are representative of their respective age groups and characterize the motor status of our sample.

After completing screening tests, participants will be asked to perform tapping tasks using a computer keyboard while sitting in a chair viewing a computer monitor. When using the button press device, participants will be asekd to press correpondeding buttons in resonse to the placement of visual stimuli (shapes) on the computer screen. This computerized task will take approximately 20 minutes to complete.

Additionally, participants will be asked to perform a manipulative dexterity task using their hands which requires participants to place pegs into a pegboard while sitting in a chair. Participants will be asked to complete this task with both their dominant and non-dominant hand. This task takes approximately 5 minutes to complete.

You will be given a duplicate copy of this informed consent after you sign this form. The approximate total time to complete the study is 30 minutes.

Confidentiality: Only a code number will identify your data. The results will be stored separately from the consent form, which includes your name and any other identifying information. At no time will your name be associated with your responses.

All information will be kept in locked file cabinets of the study investigator.

Expected Risks: The risks of participating in this study are minimal. All measures are noninvasive. Possible risks may include fatigue and tedium. The researchers will try to minimize these risks by allowing you to stop testing either temporarily or permanently if you are unable or do not wish to continue. There will be breaks during testing to allow you to rest.

Expected Benefits: You will not directly benefit from participating in this study; however, your participation will be beneficial for us to gain a better understanding of motor coordination.

Voluntary Participation: Participation in this study is voluntary. You may choose not to participate. If you do decide to participate, you can change your mind at any time and withdraw from the study without experiencing negative consequences. Refusing to participate will not involve penalty or loss of benefits.

Use of Research Results: Results will be presented in aggregate form only. No names or individually identifying information will be revealed. Results may be presented at research meetings and conferences and in scientific publications.

Future Questions: If you have any questions concerning your participation in this study now or in the future, you can contact Kaitlin Oswald at koswald@emich.edu or Jin Bo, Ph.D. at jbo@emich.edu.

This research protocol and informed consent document has been reviewed and approved by the Eastern Michigan University Human Subjects Review Committee for use from 9/5/2014 to 9/14/2015. If you have questions about the approval process, please contact UHSRC administrative co-chair at human.subjects@emich.edu or call 734-487-0042.

Consent to Participate: I have read or had read to me all of the above information about this research study, including the research procedures, possible risks, side effects, and the likelihood of any benefit to me. The content and meaning of this information has been explained and I understand. All my questions, at this time, have been answered. I hereby consent and do voluntarily offer to follow the study requirements and take part in the study.

All participants must be 18 years or older. By signing this consent form, you are confirming that you are at least 18 years old.

PRINT NAME: ____

Signatures:

________________________________ ______________________

Participant or Parents/guardians (your signature) Date

________________________________ ______________________

Investigator or Specified Designee Date

APPENDIX C
Questionnaire

Participant ID: ________________________ Date: ____________________

Please make the appropriate selections. If you do not feel comfortable answering a question, please just continue on to the next question.

1. Age: ________________________
2. Sex:

   ☐ Female ☐ Male
3. Ethnicity:

   ☐ African American ☐ Asian

   ☐ Caucasian ☐ Other (Please Specify): ______________________

   ☐ Hispanic
4. Do you take any medications regularly?

   ☐ Yes ☐ No ☐ If yes, please specify: ____________________
5. Do you have any impairments in vision?

   ☐ Yes ☐ No ☐ If yes, please specify if corrected (glasses/contacts): ____________________
6. Have you ever had any head injuries?

   ☐ Yes ☐ No ☐ If yes, please specify: ____________________
7. Do you have any bone fractures?

   ☐ Yes ☐ No ☐ If yes, please specify: ____________________
8. Have you ever been diagnosed with any of the following: Attention-Deficit Hyperactivity Disorder (ADHD), Learning Disability (LD), Developmental Coordination Disorder (DCD), or Autism Spectrum Disorder (ASD)?

   ☐ Yes ☐ No
9. Do you have experience playing an instrument for one year or more?

   ☐ Yes ☐ No ☐ If yes, please specify: ____________________
10. Do you have experience playing a sport for one year or more?

    ☐ Yes ☐ No ☐ If yes, please specify: ____________________

APPENDIX D

Edinburgh Handedness Inventory

Please indicate your preferences in the use of hands in the following activities by *putting + in the appropriate column*. Where the preference is so strong that you would never try to use the other hand unless absolutely forces to, *put ++*. If any case you are really indifferent put + in both columns.

Some of the activities require both hands. In these cases the part of the task, or object, for which hand preference is wanted is indicated in brackets.

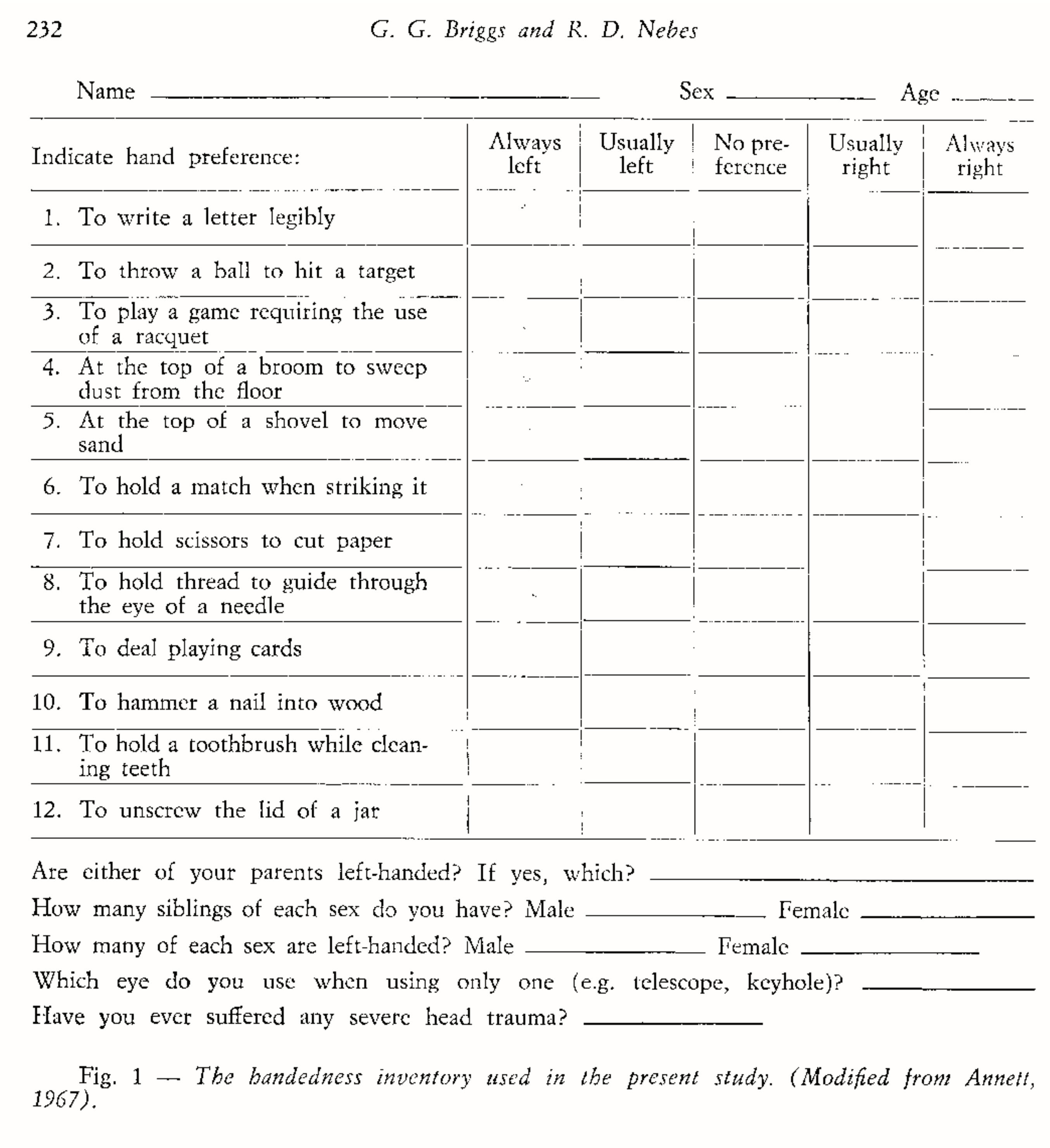
Please try to answer all the questions, and only leave a blank if you have no experience at all of the object or task.

	Left	Right
1. Writing		
2. Drawing		
3. Throwing		
4. Scissors		
5. Toothbrush		
6. Knife (without fork)		
7. Spoon		
8. Broom (upper hand)		
9. Striking Match (match)		
10. Opening box (lid)		
i. Which foot do you prefer to kick with?		
ii. Which eye do you use when using only one?		

L.Q.	Leave the spaces blank	DECLE

APPENDIX E

The Handedness Inventory



232 *G. G. Briggs and R. D. Nebes*

Name ______________________ Sex __________ Age ______

Indicate hand preference:	Always left	Usually left	No preference	Usually right	Always right
1. To write a letter legibly					
2. To throw a ball to hit a target					
3. To play a game requiring the use of a racquet					
4. At the top of a broom to sweep dust from the floor					
5. At the top of a shovel to move sand					
6. To hold a match when striking it					
7. To hold scissors to cut paper					
8. To hold thread to guide through the eye of a needle					
9. To deal playing cards					
10. To hammer a nail into wood					
11. To hold a toothbrush while cleaning teeth					
12. To unscrew the lid of a jar					

Are either of your parents left-handed? If yes, which? ______________

How many siblings of each sex do you have? Male __________ Female __________

How many of each sex are left-handed? Male __________ Female __________

Which eye do you use when using only one (e.g. telescope, keyhole)? __________

Have you ever suffered any severe head trauma? __________

Fig. 1 — *The handedness inventory used in the present study. (Modified from Annett, 1967).*

APPENDIX F

Tapping Paradigm Record Form

Participant ID: _______________________

Date: __________________ **Time:** __________________

Participant Mood Notes: ____
____
____.

Additional Notes: ____
____
____
____
____
____

Grooved Pegboard Test

Dominant Hand _____________ **Time** ________ **Drops** _ **Pegs Placed**_________ **Total** ________

Non-Dom. Hand _____________ **Time** ________ **Drops** _ **Pegs Placed**_________ **Total** ________

Tapping Paradigm Order:

1.____
2.____
3. ____
4.____
5.____

APPENDIX G

Tapping Paradigm Screen Displays