THE MOTORIC VS. PERCEPTUAL BASIS OF BIMANUAL COORDINATION

THE PERCEPTUAL VS. MOTORIC BASIS OF BIMANUAL COORDINATION IN YOUNG ADULTS AND INDIVIDUALS WITH PARKINSON'S DISEASE

By

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Dedication

For Helen Salter, you are my inspiration.

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Preamble

The research presented in this thesis investigates the motoric versus perceptual basis of bimanual coordination stability. A general introductory section provides an overview of Parkinson's disease, upper limb coordination in healthy younger and healthy older adults and individuals with Parkinson's disease, and the current views of the basis of bimanual coordination stability. Following the general introductory section are two manuscripts for the two experiments. Both experiments followed similar paradigms. Healthy young adults participated in the first experiment and individuals with Parkinson's disease and healthy older adults participated in the second experiment.

Following the presentation of the empirical work is a general discussion section. This section is intended to summarize the two experiments, to discuss potential methodological issues and to provide ideas for future experiments.

General Introduction

The majority of daily activities require the integrated performance of the two hands. The maintenance of the ability to perform coordinated movements with the upper limbs is an important component of remaining independent and enjoying a high quality of life. However, individuals with Parkinson's disease exhibit decrements in the ability to perform coordinated movements with the upper limbs (Almeida, Wishart, & Lee, 2002; Byblow, Summers, Lewis, & Thomas, 2002; Johnson, Cunnington, Bradshaw, Phillips, Iansek, & Rogers, 1998). As the disease progresses, these individuals are at risk for becoming more dependent on others, partially as a consequence of the loss of the ability to coordinate their upper limbs.

The rationale for the experiments described in this thesis is to provide a further understanding of the mechanisms of bimanual coordination in healthy young adults, which could then be applied to healthy older adults and to individuals with Parkinson's disease. This research will contribute to the current understanding of the dynamics of bimanual coordination. As well, by identifying the mechanisms underlying the bimanual coordination deficits associated with Parkinson's disease, effective rehabilitation techniques can be developed to facilitate coordinated movement. This general introduction will provide an overview of Parkinson's disease, upper limb coordination in healthy younger and older adults, and in individuals with Parkinson's disease, and the current views of the basis of bimanual coordination. In addition, this general introduction will discuss the purpose and hypotheses of the experiments described in this thesis.

1. Idiopathic Parkinson's disease

1.1 Incidence of idiopathic Parkinson's disease

Idiopathic Parkinson's disease (PD) is a progressive neurodegenerative disorder with a specific neurological and biochemical pathology but an, as yet, unknown cause (Hurtig, 2002). PD, the third most common neurological disorder after stroke and Alzheimer's disease (Morris, 2000) is characterized by a decline in motor functioning (Hurtig, 2002; Morris, 2000). In Canada, approximately 80 000 people are diagnosed with PD, with men and women affected equally (The Parkinson Foundation of Canada, 2001). The incidence of PD increases steadily after the age of 55 (Maraganore, 2002), with 1 in 1000 people over the age of 65 and 1 in 100 people over the age of 75 affected (The Parkinson Foundation of Canada, 2001). PD with onset before age 40 is uncommon (Maraganore, 2002). It is estimated that, world wide, 10 million people have PD (Morris, 2000) and as life expectancies continue to increase, it is anticipated that this number will only rise.

1.2 Symptoms of idiopathic Parkinson's disease

Movement disorders are the hallmark symptom of PD, severely compromising the ability to perform daily activities. Typical symptoms include a generalized slowing of movement (bradykinesia), prolonged movement initiation time (akinesia), decreased movement amplitude (hypometria), resistance to passive movements (rigidity), resting tremor, difficulty with balance and walking and sudden cessations of movement partway through an action sequence (freezing) (Hurtig, 2002; Morris, 2000). In particular, these impairments result in difficulties in performing simple daily tasks such as tying shoelaces, brushing teeth, washing hair, picking up a child, preparing a meal, writing, and walking.

The rate of progression and severity of PD is unpredictable and unique for each individual. Some may have symptoms for many years before a significant disability develops, whereas motor and cognitive functioning may deteriorate rapidly in others (Hurtig, 2002). Initially, signs of PD are usually confined to one side of the body, with function preserved on the contralateral side. However, with disease progression, symptoms become more severe and develop bilaterally (Hoehn & Yahr, 1967; Youdim & Reider, 1997). Consequently, individuals with PD experience difficulties performing coordinated movements with the upper limbs (Johnson et al., 1998).

1.3 Neuropathology of idiopathic Parkinson's disease

It is generally agreed that PD is the result of a progressive loss of the dopamine-producing cells in the striatum of the basal ganglia (Cunnington, Egan, O'Sullivan, Hughes, & Bradshaw, 2001; Hurtig, 2002; Iansek, Bradshaw, Phillips, Cunnington, & Morris, 1995; Nurmi, Ruottinen, Bergman, Haaparanta, Solin, Sonninen, & Rinne, 2001). Dopamine is essential in controlling the balanced excitatory and inhibitory output from the basal ganglia to the motor control regions known to control the smooth execution of voluntary movement (Alexander & Crutcher, 1990). The loss of dopamine is associated with excessive inhibitory output from the basal ganglia, thereby resulting in difficulties with the execution of voluntary movement (Iansek et al., 1995).

1.4 Upper limb coordination deficits associated with Parkinson's disease

Individuals with PD exhibit specific motor deficits when performing two simultaneous tasks with the upper limbs (Benecke, Rothwell, Dick, Day, & Marsden, 1986; Horstink, Berger, van Spaendonck, van den Bercken, & Cools, 1990; Lazarus & Stelmach, 1992; Schwab, Chafetz, & Walker, 1954; Soliveri, Brown, Jahanshahi, & Marsden, 1992). These deficits are evident when coordination performance is compared to that of healthy adults who are of a similar age. Older adults are able to perform two tasks simultaneously almost as well as when the tasks are performed separately (Spirduso, 1995). In contrast, individuals with PD are only able to perform two manual operations simultaneously when the tasks are similar or related (Stelmach & Worringham, 1988). When these individuals simultaneously perform two different tasks, which they perform well independently, they experience bradykinesia and hypometria (Brown, Jahanshahi, & Marsden, 1993; Horstink et al., 1990; Lazarus & Stelmach, 1992; Schwab, Chafetz, & Walker, 1954; Soliveri et al., 1992). Furthermore, rather than performing the two tasks simultaneously, they tend to perform one movement with one hand and then perform the second movement with the other hand. For example, individuals with PD were unable to squeeze a bulb ergograph with one hand while connecting the points of triangle with the other hand, but were able to perform both tasks separately (Schwab et al., 1954). Similarly, individuals with PD were unable to simultaneously complete the Purdue pegboard with one hand while repetitively tapping the finger of the other hand (Brown, Jahanshahi, & Marsden, 1993), isometrically contract one hand while isotonically flexing the other hand (Lazarus & Stelmach, 1992), or button a sweater while tapping the feet (Soliveri et al., 1992), but were able to perform each task well in isolation.

In the laboratory, bimanual coordination is often studied using a temporal coordination task in which continuous movements are made with the upper limbs. This task will be described in the following section.

2. Bimanual coordination

Dynamic pattern theory has provided a theoretical framework to examine bimanual coordination (Haken, Kelso, & Bunz, 1985, Jeka & Kelso, 1989; Kelso, 1984; Kelso, 1995). A tenet of this theory is that movements are self-organized as there is an intrinsic tendency to perform certain coordinated movement patterns and to be attracted to these patterns during particular conditions (Haken et al., 1985). Bimanual coordination research indicates that there are two intrinsic coordination patterns of the upper limbs that are preferred over all other coordination combinations. These patterns are referred to as in-phase and anti-phase coordination (Kelso, 1984; Schöner & Kelso, 1988; Turvey, 1990). In-phase coordination refers to symmetrical movements made simultaneously towards and away from the longitudinal axis of the body and anti-phase coordination refers to asymmetrical movements made from one side of the longitudinal axis of body to the other. These patterns are intrinsic as they typically do not require practice to be performed well in the general population (Scholz, 1990).

Interlimb coordination can be quantified by measuring relative phase, which measures the latency of one limb with respect to the other in a cyclical coordination pattern. The stability and accuracy of performance has been quantified by measuring the standard deviation and absolute mean error of relative phase, respectively (Kay, Saltzman, & Kelso, 1991). Research with young, healthy adults indicates that in-phase (relative phase = 0- degrees) and anti-phase coordination patterns (relative phase = 180-degrees) are performed with greater accuracy and greater stability then are all other phase relations (Haken et. al, 1985; Yamanishi, Kawato, & Suzuki, 1980). In particular, in-phase coordination is the more stable and accurate of the two intrinsic patterns (Byblow, Summers, Semjen, Wuyts, & Carson, 1999; Carson, 1995; Kelso, 1984; Riek, Carson, & Byblow, 1992; Summers, Semjen, Carson, & Thomas, 1995; Swinnen, Dounskaia, Verschueren, Serrien, & Daelman, 1995).

The relative stability of upper limb coordination becomes most apparent when individuals increase the frequency of performing the patterns, when they attempt to switch from one pattern to another, or when they try to learn a new coordination pattern. Increasing movement frequency affects the stability of anti-phase coordination more than it affects in-phase coordination, eventually resulting in a destabilizing of anti-phase coordination which, unless resisted, can lead to an involuntary transition from anti-phase to in-phase coordination (Schmidt & Lee, 1999; Swinnen, 2002). However, in-phase coordination does not destabilize at increased movement frequencies and involuntary transitions from in-phase to anti-phase coordination are rare (Kelso, 1984). Voluntary transitions from in-phase to anti-phase coordination take significantly longer than transitions from the less stable anti-phase pattern to the more stable in-phase pattern (Scholz & Kelso, 1990). Due to the stability of in-phase and anti-phase coordination, they act as attractor states and intermediate patterns (e.g., 90- or 45- degree coordination patterns) are difficult to perform and require extensive practice to learn (Fontaine, Lee & Swinnen, 1997; Lee, Swinnen & Verschueren, 1995; Zanone & Kelso, 1992).

Further evidence for the intrinsic tendency to perform inter-limb in-phase and anti-phase coordination is provided by studies examining performance in a variety of situations including coordination of the arms (Johnson et al., 1998; Verschueren, Swinnen, Dom, & Weerdt, 1997; Wishart, Murdoch, & Hodges, 2000), the wrists (Sullivan, Fama, Shear, Cahn-Weiner, Stein, & Zipursky, 2001), and the fingers (Cunnington et al., 2001; Geuze, 2001; Kelso, 1984; Mechsner, Kerzel, Knoblich, & Prinz, 2001). In addition, these so-called attractor patterns are more stable than all other coordination patterns in a variety of participant populations, for example, individuals with schizophrenia (Bellgrove, Bradshaw, Velakoulis, Johnson, Roger, Smith, & Pantelis, 2001; Sullivan et al., 2001), commissurotomy (Tuller & Kelso, 1989), or Huntington's disease (Brown et al., 1993) as well as older adults (Greene & Williams, 1996; Wishart et al., 2000) and individuals with PD (Almeida, et al., 2002; Johnson et al., 1998).

2.1 Older adults and bimanual coordination

Of the few studies completed on the bimanual coordination of healthy older adults, most have shown that the decline in motor functioning is selective and not absolute (Wishart et al., 2000). That is, compared to younger adults, older adults are as accurate and stable in performing in-phase coordination but perform anti-phase movements with less accuracy and consistency (Greene & Williams, 1996; Salter, Wishart, & Lee, 2001; Wishart et al., 2000; Wishart, Lee, Cunningham, & Murdoch, 2002). When moving at frequencies that are faster than preferred, older adults demonstrate increased difficulties with anti-phase coordination (Greene & Williams, 1996; Salter et al., 2001; Wishart et al., 2000) and involuntary transitions from anti-phase to in-phase coordination occur at significantly lower frequencies for older adults than for younger adults (Greene & Williams, 1996). Older adults take significantly longer to voluntarily switch between the intrinsic coordination patterns (compared to younger adults) and they exhibit greater difficulty switching from in-phase to anti-phase coordination than vice versa (Greene & Williams, 1996). In addition, healthy older adults are able to learn a new coordination pattern, but their rate of improvement is slower and their performance levels lower than healthy young adults (Swinnen, Verschueren, Bogaerts, Dounskaia, Lee, Stelmach, & Serrien, 1998; Wishart et al., 2002).

2.2 Individuals with Parkinson's disease and bimanual coordination

Individuals with PD experience problems coordinating upper limb movements. The results of the studies of individuals with PD that have investigated the integrity of the innate coordination patterns that have previously been established in young and older adults have found preservation of some pattern characteristics and degeneration of others. On a positive note, research has shown that individuals with PD display similar coordination accuracy and stability of in-phase coordination as do healthy older adults. In contrast, anti-phase coordination is performed with greater mean error and variability (Almeida et al., 2002; Geuze, 2001; Johnson et al., 1998; van den Berg, Beek, Wagenaar, & van Wieringen, 2000) and involuntary transitions from anti-phase to in-phase coordination occur at significantly lower movement frequencies as compared to healthy older adults (Byblow, Summers, Lewis, & Thomas, 2002). Individuals with PD take significantly longer to voluntarily switch between coordination patterns compared to older adults and exhibit greater difficulty in switching from in-phase to anti-phase coordination than vice versa (Almeida, 2000). Furthermore, the bimanual movements of the individuals with PD are performed with smaller amplitudes (hypometria) and with slower movement frequencies (bradykinesia) (Byblow et al., 2002; Swinnen, Van Langendonk, Verschueren, Peeters, Dom & de Weerdt, 1997). Overall, these findings suggest that with PD, the ability to perform the innate coordination patterns between the upper limbs is not lost but that these individuals have a marked problem performing anti-phase coordination.

3. What is known about the basis of upper limb coordination?

3.1 Motoric view of bimanual coordination

Despite the observation that anti-phase performance deteriorates with age and that this deterioration is exacerbated with PD, in-phase and anti-phase coordination still remain more stable than all other phase relations. Currently, there exists some controversy in the literature as to why there is an intrinsic tendency to perform these two upper limb patterns. The widely accepted motoric view suggests that the characteristics of bimanual coordination can be explained by muscular activity (Carson, Riek, Smethurst, Lison Parraga, & Byblow, 2000; Johnson et al., 1998; Kelso, 1984; Park, Collins, & Turvey, 2001; Swinnen, Jardin, Meulenbroek, Dounskaia, & Hofkens-Van Den Brandt, 1997; Swinnen, Steyvers, Van Den Bergh, & Stelmach, 2000). This view suggests that in-phase performance is the most stable and accurate of the coordination patterns because homologous muscle groups are activated simultaneously (muscular in-phase), whereas anti-phase performance is more variable because non-homologous muscle groups are activated simultaneously (muscular anti-phase). It is hypothesized that the stability of bimanual coordination is the result of an exchange of information between the hemispheres via the corpus callosum (Carson et al., 2000; Cattaert, Semjen, & Summers, 1999; Swinnen, Young, Walter, & Serrien, 1991). In particular, in-phase coordination is the most stable pattern because contraction of muscles on one side of the body causes an increase in excitability of the muscles on the contralateral side of the body, resulting in activation of homologous muscle groups. On the other hand, the literature has not addressed how this logic can be applied to the relative stability of anti-phase coordination.

3.1.1 Egocentric vs allocentric basis of the motoric view of bimanual coordination

This traditional motoric view has been revised and expanded by several of its proponents. Swinnen and colleagues have suggested that when defining in-phase and anti-phase coordination, the plane in which the movement occurs and the direction of movement should also be considered (Bogaerts, Buekers, Zaal, & Swinnen, 2002; Swinnen, 2002; Swinnen, Jardin, et al, 1997; Swinnen et al., 1998). For example, coordinated movements can be defined relative to an internal (egocentric) or external (allocentric) reference frame (Swinnen, 2002). The egocentric reference frame refers to cyclical bimanual movements made in the horizontal plane (movements made parallel to the frontal plane of the body) towards and away from the longitudinal axis of the body. With in-phase coordination, the simultaneous activation of homologous muscle groups results in the upper limbs moving in different directions whereas with anti-phase coordination, the simultaneous activation of non-homologous muscle groups results in the upper limbs moving in the same direction.

The allocentric reference frame, on the other hand, suggests limb movements that are made in the same direction are produced more accurately and consistently than movements made in different directions (Baldissera, Cavallari, & Civaschi, 1982; Baldissera, Cavallari, Marini, & Tassone, 1991; Carson et al., 2000; Kelso & Jeka, 1992; Swinnen, Jardin et al., 1997; Wenderoth & Brock, 2002). In the vertical plane (movements made orthogonal to the frontal plane of the body), cyclical upper limb movements that involve simultaneous activation of homologous muscle groups *and* movements in the same direction in extrinsic space are more accurate and stable than alternative patterns (Bogaerts et al., 2002; Park et al., 2001; Swinnen, Jardin et al., 1997; Swinnen et al., 1998). More specifically, in-phase coordination is more stable in the vertical plane than in the horizontal plane because the limbs move in the same direction and because homologous muscle groups are activated simultaneously. In contrast, during anti-phase coordination in the vertical plane, the upper limbs move in different directions and non-homologous muscular groups are activated simultaneously (Bogaerts et al., 2002; Swinnen, Jardin et al., 1997). Through a series of experiments, Swinnen et al. (1998) concluded that although movement direction is an important factor, muscular activity is more dominant in determining the stability of upper limb coordination.

3.2 Perceptual view of bimanual coordination

The motoric basis of bimanual coordination has recently been challenged by Mechsner and colleagues (Mechsner, Kerzel, Knoblich, & Prinz, 2001). They propose that the characteristics of bimanual coordination are not best explained by muscular activity but instead by how movements are perceived visually. This view suggests that the visual perceptual qualities of movement dominate over muscular activity. Specifically, movements that are visually perceived to be mirror symmetrical are preferred over alternate coordination tendencies, regardless of the muscular activation of the limbs producing the movement. They propose that in-phase coordination is the most stable and accurate of the coordination patterns because it is visually perceived to be mirror symmetrical (visually in-phase), whereas anti-phase coordination is more variable because it is visually perceived to be asymmetrical (visually anti-phase).

This visual perceptual view is based on an experiment in which participants viewed objects that rhythmically moved in different phase relationships to each other on a computer screen (Zaal, Bingham, & Schmidt, 2000). Results demonstrated that two rhythmically moving objects with an in-phase pattern (relative phase = 0- degrees) were easier to identify and were considered to be more stable than two rhythmically moving objects with an anti-phase pattern (relative phase = 180- degrees). Zaal and colleagues (2000) proposed that if participants are not able to perceive a stable pattern, then they may not be able to perform it. Therefore, the perception of an in-phase pattern may play a fundamental role in the stability of upper limb coordination.

Through a series of experiments with healthy young adults, Mechsner and colleagues (2001) demonstrated that the tendency to perform in-phase and anti-phase coordination is dependent on how the movements are visually perceived. In one experiment, participants performed bimanual finger oscillations with movement instructions visually defined with regard to the longitudinal axis of the body Movements were visually in-phase when the index finger of each hand moved in symmetry towards and away from the longitudinal axis of the body Movements were visually anti-phase when one index finger moved towards the midline of the body while the other moved synchronously away from it and vice versa. These bimanual finger movements were performed with different positions of the hands. When both palms faced up or down then visual in-phase corresponded with activation of homologous muscle groups and visual anti-phase corresponded with activation of non-homologous muscle groups. Conversely, when one palm faced up while the other faced down, visual in-phase corresponded with activation of non-homologous muscle groups and visual anti-phase corresponded with activation of homologous muscle groups. The motoric view would predict that regardless of the position of the hands, performance would be most stable with activation of homologous muscle groups. However, results revealed that regardless of the position of the hands, performance was most stable with visually in-phase movements and that increases in movement frequency resulted in involuntary transitions from visual anti-phase to visual in-phase. From these findings, Mechsner and colleagues concluded that the stability of bimanual coordination could be explained by the movements' visual perceptual qualities rather than activity of the muscles involved.

The perceptual view was further supported in another experiment in which participants performed a bimanual circle-drawing task (Mechsner et al., 2001). The goal of the task was to coordinate two flags in circular in-phase or circular anti-phase by moving the upper limbs in in-phase or anti-phase. Although the left flag and left hand movements were directly related to each other, the right flag moved at a higher frequency than the right hand. As a result, in order to coordinate the flags visually in-phase or anti-phase the participants were unable to concentrate on the movement of the hands and instead had to rely on the visual feedback provided by the flags. The motoric view would predict that regardless of the movement of the flags, performance would be most stable with activation of homologous muscle groups. The perceptual view would predict that regardless of the movement of the hands, performance would be most stable with visual in-phase coordination of the flags. Results supported the perceptual view in that performance was most stable when coordinating the flags visually in-phase. Although visual anti-phase was stable at slow movement frequencies, involuntary transitions to visual in-phase occurred with increasing frequency. These findings show the same pattern of results as dynamical pattern theory would predict but with, as Mechsner et al. would argue, a 'perceptual' task. Mechsner and colleagues concluded that the stability of in-phase performance is dependent upon visual perception rather than activation of homologous muscle groups.

In general, the work of Mechsner and colleagues (2001) has challenged the current understanding of the motoric view of bimanual coordination. However, a few methodological issues may have biased the results in favour of the perceptual view and should be considered.

3.2.1 Methodological shortcomings

Methodological shortcomings may have confounded the Mechsner et al. (2001) results in support of a perceptual view of bimanual coordination. One shortcoming is associated with the availability of visual and proprioceptive information from the upper limbs. In the first experiment, participants were unable to dissociate the visual and proprioceptive sources of feedback provided by the fingers. In the second experiment, although vision of the hands was eliminated, participants could see the movement of their upper limbs. As a result, for both experiments, it is not clear whether participants concentrated on the perceptual goal of the task or concentrated on activating the correct muscles to perform visual in- and anti-phase with the fingers or flags. Therefore, it is difficult to conclude that the perceptual qualities of the movement dominated over the muscular activity, as the perceptual view proposes.

Another potential confounding factor involved the timing requirements of the tasks used in the experiments. In the first experiment, movements were externally paced by an auditory metronome and participants completed one full cycle of movement on each beat. In the second experiment, participants began at a frequency they considered 'comfortable' and 'slow' and increased their pace to a frequency they considered 'fast' In addition, participants completed a cycle of movement at their own pace. Because frequency was internally paced and subjective, there was considerable variation in movement frequency between participants and coordination patterns. Participants may have traded speed for accuracy by performing in-phase coordination of the flags at a slower frequency in order to improve stability and accuracy. Therefore, it may appear that in-phase coordination of the flags was more stable than anti-phase coordination but this may be attributed to a speed accuracy trade-off, rather than intrinsic pattern stability.

The final methodological factor that may have affected the results is associated with the bimanual-circle drawing task. It could be argued that Mechsner et al.'s paradigm required the participants to learn new coordination patterns in order to coordinate the flags. Therefore, instead of examining the intrinsic coordination patterns, their paradigm may have assessed the dynamics of a newly learned and consciously controlled coordination pattern. It is possible that the perceptual view may be task- and methodology- specific and as a result it is unknown whether the perceptual view can be generalized to other experimental paradigms. Given these methodological issues, the results may have been biased toward a perceptual view of bimanual coordination. Therefore, further investigations need to address the basis for the characteristics of bimanual coordination. The experiments described in this thesis take into consideration these methodological limitations and examine which view (motoric or perceptual) can explain the basis of stability of bimanual coordination.

4. The motoric vs. the perceptual view of bimanual coordination in Parkinson's disease.

The perceptual view of bimanual coordination has been supported in healthy young adults with a particular experimental paradigm (Mechsner et al., 2001). However, it remains unknown whether a perceptual explanation can be extended to other participant populations and to different experimental designs and methodology Therefore, the present research examines whether the perceptual view can be replicated with a linear slide apparatus which is a task typically used to study bimanual coordination in healthy younger and older adults and in individuals with PD (Almeida et al., 2002; Salter et al., 2001, Swinnen et al., 1998; Verschueren et al., 1997; Wishart et al., 2000; Wishart et al., 2002). This research further examines whether the mechanisms of bimanual coordination are similar for healthy younger adults, healthy older adults, and individuals with PD.

Individuals with PD were chosen to test and extend the understanding of the basis of bimanual coordination because they depend on information more than younger and older adults do in order to accomplish tasks. They rely more on visual information than healthy adults to facilitate continuous movement performance (Byblow et al., 2002; Cunnington, Iansek, Bradshaw, & Phillips, 1995) and to compensate for a decline in proprioception (Schneider, 1991, Schneider, Diamond, & Markham, 1987; Swinnen et al., 2000). These findings suggest that the perceptual qualities of movement may dominate over muscular activity in individuals with PD. If so, support for the perceptual view of bimanual coordination may be found. Individuals with PD demonstrate a destabilization of anti-phase coordination (Almeida et al., 2002; Byblow et al., 2002; Johnson et al., 1998). If the perceptual view is the basis of bimanual coordination stability, then theoretically, the performance of anti-phase coordination by individuals with PD would benefit from visual feedback that was visually in-phase.

5. Overall purpose and experimental task

The overall purpose of the following two experiments presented in this thesis was to determine whether the characteristics of bimanual coordination are best explained by the widely accepted motoric view or by the recently proposed perceptual view. That is, are in-phase and anti-phase coordination patterns preferred over all other phase relations due primarily to the activation of homologous muscle groups or to how the patterns are visually perceived? More specifically, is in-phase coordination more stable than anti-phase coordination because homologous muscle groups are activated simultaneously or because the movement is visually perceived to be mirror symmetrical?

In the present experiments, the motoric and perceptual views of bimanual coordination were contrasted by modifying a linear slide apparatus typically used in the study of bimanual coordination (Almeida et al., 2002; Fontaine et al., 1997; Salter et al., 2001; Swinnen et al., 1998; Verschueren et al., 1997; Wishart et al., 2000). For each experiment, the goal of the task was to coordinate the two flags in in-phase (visual in-phase) or in anti-phase (visual anti-phase) patterns by moving the upper limbs linearly and horizontally in in-phase (muscular in-phase) or anti-phase (muscular anti-phase) coordination. The comparison of the motoric versus perceptual view was based on the relationship between the movement of the flags and the movement of the upper limbs. The flags could be attached to the apparatus to become compatible or incompatible to the movement of the upper limbs. In the compatible condition, the visual information provided by the movement of the flags corresponded with the movement of the upper limbs (e.g., muscular in-phase corresponded with visual in-phase and muscular anti-phase corresponded to visual anti-phase). In the incompatible condition, a 180-degree transformation between the right flag and the right hand dissociated the visual information provided by the movement of the flags from the movement of the upper limbs (e.g., muscular in-phase corresponded with visual anti-phase and muscular anti-phase corresponded with visual in-phase).

6. Purpose and hypothesis of Experiment 1 and 2

6.1 Experiment 1

Healthy young adults were tested to determine whether the perceptual or motoric views of bimanual coordination would better explain the intrinsic movement characteristics by using a typical coordination paradigm. Support for the motoric view would be found if, regardless of the coordination of the flags, muscular in-phase was more stable than muscular anti-phase. Conversely, support for the perceptual view would be obtained if, regardless of the coordination of the hands, visual in-phase was more stable than visual anti-phase.

6.2 Experiment 2

In Experiment 2, individuals with PD and healthy age- and sex- matched controls performed the bimanual task with the compatible or incompatible visual feedback. In general, it was predicted that the coordination patterns of the individuals with PD would be more variable, less accurate, performed with smaller amplitudes, and performed with slower movement frequencies compared to those of healthy older adults. The motoric view would be supported if, regardless of the coordination of the flags, muscular in-phase was more stable than muscular anti-phase. In contrast, the perceptual view would be supported if, regardless of the coordination of the hands, visual in-phase would be more stable than visual anti-phase. If the perceptual view was supported, then it was expected that muscular anti-phase coordination by individuals with PD would benefit from visual feedback that was visually in-phase.

7. Summary

The purpose of this thesis is to investigate the basis of the preferred phase relationship stability in bimanual coordination in young adults, healthy older adults, and individuals with PD. A better understanding of the mechanisms of bimanual coordination patterns would be beneficial on a theoretical and a practical level. This research will contribute generally to the theoretical understanding of the dynamical systems theory of bimanual coordination and more specifically, toward an understanding of the control of coordinated movements in PD populations. Ultimately, it is hoped that this research may aid in the development of rehabilitative programs. For example, if the perceptual view of bimanual coordination is supported and incompatible visual information enhances motor performance, then this understanding could be the basis for rehabilitation interventions. Regardless, clarification of the mechanisms of bimanual coordination in PD will aid in the development of interventions. Therefore, the rationale for the experiments presented in this thesis is to provide insight into the mechanisms of upper limb coordination by examining the motoric and perceptual views of bimanual coordination.

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The Basis of Bimanual Coordination in Healthy Young Adults: The Perceptual versus Motoric View

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Abstract

A recent study (Mechsner, Kerzel, Knoblich, & Prinz, 2001) suggested that in-phase coordination is the most stable bimanual coordination pattern because of its perceptual qualities and not because homologous muscle groups are activated simultaneously (as previous research suggests). The present experiment investigated whether the basis of preferred phase relationship stability in bimanual coordination in healthy young adults is perceptual or motoric in nature. Twenty right-handed healthy young adults (M age= 19.5) performed continuous horizontal linear movements at 1.5 and 2.0 Hz. The goal of the task was to move two flags visually in-phase or visually anti-phase by coordinating the upper limbs in in-phase or anti-phase. In a compatible condition, the visually perceived movement direction of the flags (e.g., visual in-phase) corresponded to the movement of the upper limbs (e.g., muscular in-phase). In an incompatible condition, the visually perceived movement direction of the flags (e.g., visual in-phase) was opposite to the movement of the upper limbs (e.g., muscular anti-phase). If the basis of bimanual coordination is motoric, then regardless of the visual information provided by the movement of the flags, muscular in-phase would be more stable than muscular anti-phase. If the basis of bimanual coordination is perceptual, then regardless of the movement of the upper limbs, in-phase visual information provided by the movement of the flags would be more stable than anti-phase visual information. Measures of relative phase accuracy and stability and movement amplitude and frequency provided support for the motoric view of bimanual coordination. In addition, with incompatible visual feedback, muscular anti-phase coordination destabilized while

muscular in-phase remained stable. These findings strongly support the motoric view and provide potential support for the perceptual view of bimanual coordination. In addition, the findings emphasize the importance of compatibility between upper limb coordination and visual feedback, particularly during muscular anti-phase coordination.

The Basis of Bimanual Coordination in Healthy Young Adults: The Perceptual versus Motoric View

The majority of activities performed daily require some degree of coordination between the upper limbs (e.g., tying shoelaces, typing, washing hair, and driving). These tasks require that the hands and arms to work together, coordinating their movements to achieve the goals of the task. In order to understand the basic characteristics of the interlimb coordinated movements that underlie these functional tasks, quantifiable and controllable laboratory tasks have been devised.

Dynamical pattern theory has provided a viable theoretical framework to examine upper limb coordination (Haken, Kelso, & Bunz, 1985). A tenet of this theory is that during coordinated movements of the upper limbs in the horizontal plane (parallel to the frontal plane of the body), there is an intrinsic tendency to perform one of two coordination patterns (Kelso, 1984; Schöner & Kelso, 1988; Turvey, 1990; Yamanishi, Kawato, & Suzuki, 1980). These patterns, referred to as in-phase and anti-phase coordination, are intrinsic, as they do not require practice to be performed well (Scholz, 1990). In-phase coordination refers to symmetrical movements made simultaneously with both upper limbs towards and away from the longitudinal axis of the body, whereas anti-phase coordination refers to both upper limbs simultaneously moving from one side of the longitudinal axis of the body to the other, and always in the same direction.

A common method of quantifying coordinated movement between the two limbs is by measuring relative phase. This measurement describes the latency of one limb with respect to the cycle of the other limb during a cyclical coordination pattern. In-phase coordination is quantified by 0- degrees relative phase and anti-phase coordination by 180- degrees relative phase. The stability and accuracy of coordinated performance can be quantified by measuring the standard deviation and absolute mean error of relative phase, respectively (Kay, Saltzman, & Kelso, 1991). Research with healthy young adults indicates that these two intrinsic coordination patterns are more stable and more accurate than all other phase relations, with in-phase coordination being the more stable and accurate of the two (Byblow, Chua & Goodman, 1995; Carson, 1995; Kelso, 1984; Riek, Carson & Bylow, 1992; Summers, Semjen, Carson, & Thomas, 1995; Swinnen, Dounskaia, Verschueren, Serrien, & Daelman, 1995).

The relative stability of these coordination modes becomes apparent when individuals perform the patterns at frequencies faster than preferred, when they attempt to switch from one pattern to another, or when they try to learn a new coordination pattern. Increasing movement frequency affects the stability of anti-phase coordination more than it affects in-phase coordination, eventually resulting in a destabilization of anti-phase coordination (Byblow et al., 1995; Kelso, 1984; Lee, Blandin & Proteau, 1996; Riek et al., 1992; Schmidt & Lee, 1999; Swinnen, 2002). Depending on task instructions, increasing movement frequency may eventually result in an involuntary transition from anti-phase to in-phase coordination (Kelso, 1984). However, involuntary transitions from in-phase to anti-phase coordination are rare (Kelso, 1984). The greater stability of in-phase coordination makes voluntary switches from in-phase to anti-phase coordination more difficult (as measured by movement time) than voluntary switches in the reverse direction (Byblow, Summers, Semjen, Wuyts, & Carson, 1999; Carson, Byblow, Abernethy, & Summers, 1996; Scholz & Kelso, 1990). Due to the stability of in-phase and anti-phase coordination, intermediate patterns are difficult to perform and require extensive practice to learn (Fontaine, Lee, & Swinnen, 1997; Lee, Swinnen, & Verschueren, 1995; Zanone & Kelso, 1992).

Currently, there exists a controversy in the literature as to why in-phase and anti-phase coordination are preferred over all other phase relations. The widely accepted motoric view suggests that the preferred phase relationship stability in bimanual coordination is explained by muscular activity (Carson, Riek, Smethurst, Lison Parraga, & Byblow, 2000; Kelso, 1984; Park, Collins, & Turvey, 2001; Swinnen, Jardin, Meulenbroek, Dounskaia, & Hofkens-Van Den Brandt, 1997; Swinnen, Steyvers, Van Den Bergh, & Stelmach, 2000; Swinnen, Van Langendonk, Verschueren, Peeters, Dom, & de Weerdt, 1997). This view suggests that in-phase performance is the most stable and accurate of all possible coordination tendencies because homologous muscle groups are activated simultaneously (muscular in-phase) whereas; anti-phase performance is more variable because non-homologous muscle groups are activated simultaneously (muscular anti-phase).

This motoric view of bimanual coordination has recently been challenged by Mechsner, Kerzel, Knoblich, and Prinz (2001). They propose that the characteristics of bimanual coordination are not explained by muscular activity but rather by how the movements are visually perceived. The perceptual view stems from research showing that rhythmically in-phase objects were visually perceived to be more stable than rhythmically anti-phase objects (Zaal, Bingham, & Schmidt, 2000). This original research suggests that the visual perception of the phase relationship between two objects may play a fundamental role in the stability of interlimb coordination (Zaal et al., 2000).

Mechsner et al.'s (2001) perceptual view of bimanual coordination suggests that the perceptual qualities of the movement dominate over muscular activity. Specifically, movements that are perceived visually to be mirror symmetrical are preferred over alternate coordination tendencies, regardless of the movement of the limbs producing the movement. For instance, in-phase coordination is the most stable of the coordination patterns because it is visually perceived to be mirror symmetrical (visually in-phase), whereas anti-phase coordination is more variable than in-phase because it is visually perceived to be asymmetrical (visually anti-phase).

Mechsner et al. (2002) provided support for their perceptual view of bimanual coordination through a series of experiments with healthy young adults. Three experimental paradigms were used: a finger oscillation task, a bimanual finger-tapping task and a bimanual circle drawing task, in which the goal for each task was visually defined. All experiments showed that regardless of the movement of the effector, performance was most stable with movements that were visually in-phase. In addition, increases to movement frequency resulted in involuntary transitions from visual anti-phase to visual in-phase coordination. Based on these findings, Mechsner et al. (2001) concluded that the visual perceptual qualities of the movement dominate over muscular activity.

There are a few methodological issues associated with the experiments conducted by Mechsner et al. (2001) that may have biased their results. One shortcoming was that participants were able to see the movement of their upper limbs. Therefore, it is not clear whether participants concentrated on the visual perceptual goals of the task or concentrated on coordinating the effectors (e.g., fingers) in order to perform movements that were visually in-phase or visually anti-phase. Another potential confounding factor involved the timing requirements of the tasks. The finger oscillation and bimanual finger tapping tasks were externally paced by an auditory metronome. However, the bimanual circle drawing task was internally paced resulting in considerable variation in movement frequency between participants, between coordination patterns and between compatibility conditions. In an attempt to improve stability and accuracy of movements that were visual in-phase, participants may have performed this pattern at a slower movement frequency. Therefore, it may have appeared that visual in-phase was more stable than visual anti-phase. However, this may be attributable to a speed-accuracy trade off.

In general, despite these methodological limitations, this perceptual view has challenged the current understanding of the motoric basis of bimanual coordination. The perceptual view has been successfully supported with healthy young adults and with specific experimental paradigms (Mechsner et al., 2001). However, it is unknown whether the perceptual view can be extended to a different experimental task that addresses the methodological issues presented in the Mechsner et al. experiments. The impetus for the present experiment was to determine whether the basis of bimanual coordination is perceptual or motoric, with a task typically used to study bimanual coordination, such as a linear slide apparatus (Almeida, Wishart, & Lee, 2002; Hodges & Franks, 2002; Salter, Wishart, & Lee, 2001; Swinnen, Verschueren, Bogaerts, Dounskaia, Lee, Stelmach & Serrien, 1998; Verschueren, Swinnen, Dom, & de Weerdt, 1997; Wishart, et al., 2000; Wishart, Lee, Cunningham, & Murdoch, 2002).

The purpose of this experiment was to determine whether the characteristics of bimanual coordination are better explained by the widely accepted motoric view or by the recently proposed perceptual view. The motoric and perceptual views of bimanual coordination were contrasted by requiring participants to perform tasks executed on a linear slide apparatus. The goal of the task was to coordinate two flags in in-phase (visual in-phase) or anti-phase (visual anti-phase) by moving the upper limbs continuously linearly and horizontally in in-phase (muscular in-phase) or anti-phase (muscular anti-phase) coordination. The comparison of the motoric versus perceptual view was based on the relationship of the movement of the flags and the movement of the upper limbs. The flags could be attached to the apparatus to become compatible or incompatible with the movement of the upper limbs. In the compatible condition, the visual information provided by the movement of the flags corresponded with the movement of the upper limbs (e.g., muscular in-phase corresponded with visual in-phase and muscular anti-phase corresponded with visual anti-phase). In the incompatible condition, a 180- degree transformation between the right flag and the right hand dissociated the visual information provided by the movement of the flags with the movement of the upper limbs (e.g., muscular in-phase corresponded with visual anti-phase and muscular anti-phase corresponded with visual in-phase).

Movements were externally paced at a slow (1.5 Hz) and fast (2.0) frequency. It was predicted that support for the motoric view of bimanual coordination would be obtained if regardless of the visual information provided by the movement of the flags, muscular in-phase was more stable than muscular anti-phase coordination. Furthermore, muscular in-phase would remain stable with increasing movement frequency while muscular anti-phase performance would deteriorate. These findings would support previously reported studies in favour of the motoric view of bimanual coordination (i.e., Kelso, 1984; Swinnen et al., 1997; Swinnen et al., 2000). In contrast, it was predicted that support for the perceptual view of bimanual coordination would be obtained if regardless of the coordination of the upper limbs, movements that were visually in-phase would be more stable than movements that were visually anti-phase. Furthermore, visually in-phase movements would remain stable with increasing movement frequency and visual anti-phase performance would deteriorate.

Methods

Participants

Twenty-one (12 female, 9 male) young adults recruited from an undergraduate Kinesiology course at McMaster University (M age=19.5 years, range = 19-23 years) volunteered to participate in this experiment. One participant was eliminated from data analyses due to equipment problems, hence only the data from 20 of the 21 participants was included in the statistical analyses. Participants were free from neurological, cognitive, and upper limb problems and had not previously participated in a similar experiment. All participants read and signed a consent form prior to testing and received an honorarium of $10.00 (Cdn). This experiment received ethical approval from the Research Ethics Board at McMaster University.

All participants were strongly right-handed (M=26, range=23-27), as determined by the Waterloo Handedness Questionnaire (Bryden, 1977) (Appendix). The Minnesota Manual Dexterity Turning test was performed to assess interlimb coordination (American Guidance Services, 1969; Lafayette Instrument Company). All participants were within age-expected norms on this test.

Apparatus and Task

The goal of the task was to coordinate the movement of the two flags in visual in-phase or visual anti-phase by continuously moving two slide carriages linearly and horizontally with the upper limbs. The slide carriages were mounted on ball bearing casings and slid horizontally and in front of the participant's torso. Each slide had an 11 cm plastic molded handgrip bolted vertically to the middle of its' surface. The apparatus was secured to a table with double sided tape and C-clamps.

Participants sat on a height-adjustable, non-swivel chair with their body midline centered between the two sliding devices. To move the slide carriages, participants grasped the handgrips with their hands without resting their wrists on the slide carriage. The seat height was adjusted so that when subjects grasped the handgrips, their elbows were flexed to an angle of approximately 90- degrees.

The slide carriages and the participants' hands were hidden from view by a horizontal wood platform that was placed 18 cm above the slide carriages (Figure 1). To prevent participants from watching their upper limb movements, a cloth bib extended from the proximal edge of the wood platform and was secured with safety pins behind the participants' neck. The cloth bib did not interfere with the movements of the upper limbs. Visual feedback was provided by two vertical fluorescent yellow flags (2 cm wide, 10 cm high) located 1 cm beyond the distal edge of the wood platform. In the compatible condition, one flag was attached directly to each slide carriage so that the movements of the flags corresponded to the movement of the hands. For example, muscular in-phase and muscular anti-phase corresponded with visual in-phase and visual anti-phase, respectively. In the incompatible condition, the left flag was attached directly to the left side carriage so the movement of the left flag corresponded to the left hand. The right flag extended from a chain and pulley system that was attached to the right slide carriage so that the movement of the right hand and right flag was transformed by 180-degrees. Therefore, in the incompatible condition, the visual information provided by the movement of the flags was opposite to the movement of the upper limbs. For example, muscular in-phase corresponded with visual anti-phase and muscular anti-phase corresponded with visual in-phase (Figure 2). Depending on the compatibility condition, the right flag was either attached to the slide carriage (compatible condition) or the chain and pulley system (incompatible condition).

Two 16 cm regions were marked on the wood platform directly in front of the flags, to indicate the boundaries between which the flags were to be moved. The points closest to the body midline were referred to as the “in” positions and the maximum lateral points were referred to as the “out” positions. These “in” and “out” markers were visible to the participants throughout the experiment. Each slide carriage could be moved a maximum horizontal distance of 22 cm (i.e., 3 cm beyond the amplitude goal for both the "in" and "out" positions). The total distance between the "in" positions for each limb was 20 cm and the total distance between the "out" positions for each limb was 52 cm (the two 16 cm regions plus the 20 cm between the two "in" positions).

To encode the displacement of the upper limbs and to measure relative phase, linear potentiometers (BEI Electronics Company, model 612R12KL.08) were attached in parallel to the slide carriages. An A-D converter transferred the information from these linear potentiometers to a microprocessor. Participants were asked to perform one complete cycle of the respective movement pattern in time with an auditory metronome. The LabWindows software program (National Instruments Corporation) was customized to control the initiation and termination of each trial, the frequency of the metronome, and to record displacement data over time at 200 Hz. The auditory metronome signal was heard through earphones attached to a tone generator (Lafayette Instrument Company).

Procedure

The goal of the task was to coordinate the movement of two flags by continuously moving two slide carriages linearly and horizontally with the hands, in the requested movement pattern at the specified frequencies. Two bimanual coordination patterns (in-phase and anti-phase) were performed at slow (1.5 Hz) and fast (2.0 Hz) frequencies (as paced by an external metronome) with compatible or incompatible visual feedback. These eight conditions were performed four times for a total of 32 trials. The length of each trial was 20 s and the inter-trial interval was approximately 15 s. The total duration of the experiment, including instructions and collection of demographic information and motor characteristics was approximately 45 minutes.

Irrespective of the compatibility condition, task instructions were related to the movement of the flags. For example, visual in-phase required both the left and right flags to move away from and toward the body midline, simultaneously. Visual anti-phase required the left flag to move towards the midline of the body while the right flag moved away from it, and vice versa. These patterns were described both verbally using a standard set of instructions and through demonstration by the experimenter using two model flags. For the incompatible condition, no reference was made to the 180- degree transformation between the right flag and right hand.

Participants initially practiced in-phase coordination at a frequency they considered to be comfortable and that would allow for their best performance. The practice session took approximately 5 minutes and finished once participants performed within 15- degrees of the intended phase relationship. All participants were able to perform the requested pattern following practice. The auditory metronome was then provided through the earphones and described as an aid to help pace the desired movement frequency. Participants practiced one trial at 1.0 Hz in order to familiarize themselves with the metronome. They then practiced one trial each at 1.5 Hz and 2.0 Hz For each beat of the metronome, participants were required to move both flags one complete cycle (i.e., from the 'in' positions to the 'out' positions and back to the 'in' positions). For in-phase coordination, they were asked to have both flags at the 'in' position coincident with each beat of the metronome. For anti-phase coordination, they were asked to have the left flag at the 'in' position and the right flag at the 'out' position on the metronome beat. Participants were instructed to move the flags in a rhythmic, fluid manner without stopping, and to maintain their pace with the metronome beat. In addition, they were instructed to keep the flags between the amplitude boundaries.

Further instructions were given to 'stay' with the coordination pattern in which participants started throughout the trial. If participants made an involuntary transition away from the intended coordination pattern they were to try and reacquire the original pattern.

Throughout the experiment the participants were reminded to concentrate on the goal of coordinating the flags visually in-phase or visually anti-phase. In addition, participants were reminded to keep in time with the metronome beat. After completing each compatibility condition, participants were ask to describe what they focused their attention on during the trials.

Although it was expected that the compatible condition would yield similar results to previous findings, it was necessary to include this condition to ensure that in-phase and anti-phase coordination could be reproduced with the present experimental set-up[1]. It was possible that either compatibility condition would affect the ability to perform the other compatibility condition. In order to eliminate an effect of order of compatibility

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[1] Mechsner et al., (2001) did not include an equivalent 'compatible' condition for the circle drawing task.

conditions, half the participants (n=10) performed the compatible condition followed by the incompatible condition while the other half performed the incompatible condition followed by the compatible condition.

Participants performed 16 compatible and 16 incompatible condition trials, for a total of 32 trials. Within each compatibility condition, bimanual coordination patterns were counterbalanced for order (ABBA BAAB). A 1.5 Hz trial was always followed by a 2.0 Hz trial of the same coordination pattern. Therefore, for each compatibility condition, four trials were collected for each coordination pattern at each frequency. All participants were scheduled a 15 minute rest between compatibility conditions, at which point they completed the Waterloo Handedness Questionnaire (Bryden, 1977). During this time and unbeknown to the participants, the right flag was removed from the chain and pulley system and reattached to the slide carriage for the compatible condition or removed from the slide carriage and reattached to the chain and pulley system for the incompatible condition.

Data Analyses

Data were transferred from Lab Windows to DaDisp software program for analyses. Relative phase between the *movement of the hands* was used to measure interlimb coordination. This measure captures the relative time at which one limb advances through its movement cycle in relation to the advancement of the other limb through its cycle during a continuous task. To compute relative phase, the velocities and amplitude of the right and left limbs were rescaled to the interval (-1, 1) for each cycle of oscillation. The phase angles for each limb and a continuous estimate of relative phase was computed using the formula developed by Scholz and Kelso (1989, p. 129).

$$\Phi = \tan^{-1}[dX_R/dt)/X_R] - \tan^{-1}[dX_L/dt)/X_L],$$

where Φ is the relative phase between limbs for each sample, X is the position of the limb within a cycle rescaled to the interval (-1,1), (dX/dt) refers to the normalized instantaneous velocity, and R and L are the right and left limbs, respectively. The mean of the relative phase angle over each cycle provided a measure of average relative phase for a trial. In the compatible condition, muscular in-phase and anti-phase coordination corresponded with limb relative phase measures of 0- and 180- degrees, respectively. In the incompatible condition, visual in-phase (muscular anti-phase) and visual anti-phase (muscular in-phase) corresponded with limb relative phase measures of 180- and 0-degrees, respectively. In the interest of consistency, all results are reported with respect upper limb coordination.

To quantify accuracy of relative phase, the absolute mean error score was calculated as the unsigned difference between the observed mean and the goal relative phase (0- or 180- degrees) for each trial; the more accurate the performance, the lower the absolute mean error score. The standard deviation of the individual measures of relative phase about the scores that comprised a trial mean provided a measure of consistency (coordination stability); the lower the score, the more consistent the performance. Overall performance error of relative phase was measured using root mean square error (RMSE), calculated using the formula:

$$RMSE = \sqrt{\text{standard deviation of relative phase}^2 + \text{absolute mean error of relative phase}^2}$$

The observed movement frequency and amplitude were analyzed to provide an average of movement speed and amplitude of movement during each trial.

Involuntary phase transitions were identified by the point at which relative phase first deviated from the intended pattern by more than ±30 degrees (which is approximately equivalent to twice the standard deviation under most of the anti-phase conditions examined in Experiment 1 in Wishart et al., 2000) for a minimum of 2 s.

Statistical analyses were performed using analyses of variance (ANOVA). All ANOVA's were mixed designs, with Order of presentation of the compatibility conditions (incompatible-compatible, compatible-incompatible) as the between-group factor and all other variables as within-group factors. Relative phase was analyzed by a 2 Condition (compatible, incompatible) X 2 Phase (muscular in-phase, muscular anti-phase) X 2 Frequency (1.5, 2.0 Hz) ANOVA. Frequency and amplitude of movement was analyzed using a 2 Condition (compatible, incompatible) X 2 Phase (muscular in-phase, muscular anti-phase) X 2 Frequency (1.5, 2.0 Hz) X 2 Hand (left, right) mixed design. Tukey's HSD post hoc comparisons were performed on all significant effects and interactions. For all tests, alpha was set at .05.

If the motoric view is the basis of bimanual coordination, then it was predicted that there would be a main effect for Phase, in that muscular in-phase would be more stable and accurate than muscular anti-phase. A main effect related to Condition was not expected. It was hypothesized that there would also be a two-way interaction between Phase and Frequency, with muscular anti-phase becoming less stable and inaccurate at the faster frequency but muscular in-phase remaining equally stable and accurate at both frequencies. If the perceptual view is the basis of bimanual coordination, it was hypothesized that there would be a three-way interaction between Condition, Phase, and Frequency. Specifically during the compatible condition, muscular in-phase would be more stable than muscular anti-phase but during the incompatible condition, muscular anti-phase would be more stable than muscular in-phase.

Results

Relative phase accuracy: Statistical analysis of the absolute mean error of relative phase (accuracy) revealed significant main effects for Phase [F (1, 18) = 81.69, p < .05], Condition [F (1, 18) = 20.94, p = < .05], and Frequency [F (1, 18) = 25.94, p < .05]. Overall, the absolute mean error of relative phase was significantly greater for muscular anti-phase (M= 26.1°) than for muscular in-phase coordination (M= 9.2°). This effect is consistent with previous studies (Kelso, 1984). The compatible condition (M= 14.6°) was performed with significantly greater accuracy than the incompatible condition (M= 21.5°) and trials at the slower movement frequency (M= 15.5°) were performed with significantly greater accuracy than the faster movement frequency (M= 20.5°).

The ANOVA revealed significant two-way interactions for Condition X Phase [F (1, 18) = 23.28, p < .05] and Phase X Frequency [F (1, 18) = 28.58, p < .05]. Post hoc comparisons of the Condition x Phase interaction confirmed that muscular anti-phase was significantly less accurate during the incompatible condition (M= 33.2°) than the compatible condition (M= 19.5°), whereas muscular in-phase was performed with relatively equal accuracy for both compatibility conditions ($\underline{M}$= 10.2°, 7.7°, respectively). For the Phase x Frequency interaction, post hoc analysis revealed that the difference between relative phase accuracy for the 1.5 and 2.0 Hz trials was negligible for muscular in-phase ($\underline{M}$= 8.7°, 8.7°, respectively) whereas, muscular anti-phase was significantly less accurate at 2.0 Hz ($\underline{M}$= 31.1°) than at 1.5 Hz ($\underline{M}$= 22.4°).

Relative phase standard deviation: Similar main effects and interactions observed for absolute mean error of relative phase were observed for the standard deviation (stability) of relative phase. Overall, the compatible condition ($\underline{M}$= 10.2°) was significantly more stable than the incompatible condition ($\underline{M}$= 19.4°) [$\underline{F}$ (1, 18) = 46.7, $\underline{p} < .05$], and muscular in-phase ($\underline{M}$= 7.6°) was significantly more consistent than muscular anti-phase coordination ($\underline{M}$= 22.0°) [$\underline{F}$ (1, 18) = 140.32, $\underline{p} < .05$]. A main effect for Frequency [$\underline{F}$ (1, 18) = 17.27, $\underline{p} < .05$] indicated that an overall loss of stability was associated with the demands of increasing movement frequency (1.5 Hz $\underline{M}$= 13.2° and 2.0 Hz $\underline{M}$= 16.4°).

A two-way interaction between Condition and Phase [$\underline{F}$ (1, 18) = 64.5, $\underline{p} < .05$] was significant. Post hoc comparisons revealed that while muscular in-phase was equally stable for both compatibility conditions (compatible $\underline{M}$= 6.2° and incompatible $\underline{M}$= 9.0°), muscular anti-phase was significantly less stable for the incompatible ($\underline{M}$= 29.9°) than the compatible condition trials ($\underline{M}$= 14.1°).

An interaction between Phase and Frequency [$\underline{F}$ (1, 18) = 20.71, $\underline{p} < .05$] revealed that muscular in-phase was performed with equal stability at both movement frequencies (1.5 Hz $\underline{M}$= 7.6° and 2.0 Hz $\underline{M}$= 7.6°), whereas muscular anti-phase was performed with significantly greater variability at the faster than the slower movement frequency (1.5 Hz M= 18.8° and 2.0 Hz M= 25.2°). Therefore, stability in bimanual motor performance was associated with increased accuracy of relative phase.

Root Mean Square Error of Relative Phase: Analysis of overall relative phase performance error (RMSE) revealed similar significant main effects and interactions as those found for accuracy and stability of relative phase. Main effects for Condition [F (1, 18) = 31.00, $p < .05$], Phase [F (1, 18) = 107.83, $p < .05$] and Frequency [F (1, 18) = 23.95, $p < .05$] were obtained. Significantly greater performance error was associated with the incompatible (M= 28.9°) compared to the compatible condition (M= 16.9°), with muscular anti-phase (M= 33.7°) compared to muscular in-phase coordination (M= 12.1°), and with the faster (M= 25.6°) compared to the slower movement frequency (M= 20.2°).

A two-way interaction between Phase and Frequency [F (1, 18) = 26.07, $p < .05$] revealed that while there was a negligible difference between performance error for muscular in-phase at both frequencies (1.5 Hz M= 12.1° and 2.0 Hz M= 12.2°), muscular anti-phase coordination was performed with significantly greater error for the 2.0 Hz (M= 39.5°) compared to the 1.5 Hz (M= 27.8°) frequency trials.

A two-way interaction between Condition and Phase [F (1, 18) = 43.46, $p < .05$] was also significant (Figure 3). Post hoc comparisons confirmed that for muscular in-phase coordination, there was no significant difference in performance error between each compatibility condition (compatible M= 11.3° and incompatible M= 14.6°). For muscular anti-phase coordination, significantly greater performance error was associated with the incompatible condition (M= 45.0°) compared to the compatible condition (M=

23.8°). Therefore, muscular anti-phase was adversely affected by in-phase visual information while muscular in-phase coordination was unperturbed by anti-phase visual information.

All three measures of relative phase failed to reveal any significant main effects or interactions associated with Order. Regardless of which compatibility condition was performed initially, subsequent performance of the other compatibility condition was not affected. That is, performing the coordination patterns with compatible visual feedback did not adversely affect the ability to subsequently perform the patterns with a 180-degree transformation and vice versa.

All three measures of relative phase approached conventional levels of significance for an interaction between Condition, Phase, and Frequency (e.g., RMSE [$F(1,18) = 4.07$, $p = .058$]) (Figure 4). This three-way interaction indicates that for the compatible condition muscular in-phase (M= 10.2°) and muscular anti-phase (M= 19.6°) were performed with equivalent relative phase error for the 1.5 Hz trials. Muscular in-phase coordination was performed equally well at both movement frequencies (2.0 Hz M= 10.5°), whereas muscular anti-phase coordination was performed with greater error for the faster (M= 27.6°) than the slower (M= 19.5°) movement frequency. Results from the incompatible condition suggest that in general, muscular anti-phase was performed with greater error than muscular in-phase. Muscular in-phase was performed with equivalent error for both movement frequencies (1.5 Hz M= 14.52° & 2.0 Hz M= 14.06°), whereas muscular anti-phase coordination was performed with greater error during the faster (M= 52.6°) than the slower (M= 37.5°) movement frequency. This marginally significant three-way interaction indicated that compared to the compatible condition, muscular anti-phase was *less* accurate and *less* stable with visual information that was visual in-phase. However, incompatible visual anti-phase information did not destabilize muscular in-phase performance.

Amplitude: The target amplitude was 16 cm for the right and left hands. The analysis of observed movement amplitude resulted in significant main effects for Phase [F (1,18) = 15.53, p < .05] and Hand [F (1, 18) = 75.49, p < .05]. Significantly larger amplitudes were observed for muscular in-phase (M= 14.0 cm) compared to muscular anti-phase coordination (M= 13.5 cm) and for the dominant right hand (M= 14.6 cm) compared to the non-dominant left hand (M= 12.9 cm). A main effect for Frequency indicated that an increase in movement frequency was associated with a significant decrease in movement amplitude [F (1, 18) = 10.34, p < .05] (1.5 Hz M= 13.9 cm and 2.0 Hz M= 13.6 cm).

Statistical analysis yielded a significant interaction for Phase x Frequency x Hand [F (1, 18) = 4.5, p < .05] (Figure 5). Post hoc analysis confirmed that significantly larger amplitudes were produced by the dominant, right hand than by the non-dominant, left hand. Overall, the largest amplitude for both hands was produced during muscular in-phase coordination trials at the slower movement frequency and the smallest amplitude was produced during muscular anti-phase coordination at the faster movement frequency. Therefore, both hands were closer to the target amplitude during performance of the most stable coordination pattern at the slower movement frequency.

There was no main effects or interactions with compatibility Condition on amplitude.

Frequency: The target movement frequencies were 1.5 Hz (slow) and 2.0 Hz (fast). A main effect for Frequency confirmed that the difference between the two frequencies was significant (M= 1.5 Hz and 1.9 Hz, respectively). Main effects for Condition [F (1, 18) = 12.61, $p < .05$] and Phase [F (1, 18) = 19.6, $p < .05$] indicated that the more stable the coordination pattern or compatibility condition, the faster the movement frequency. Overall, the compatible condition was performed at a significantly faster frequency than the incompatible condition (M= 1.7 and 1.7 Hz, respectively) and muscular in-phase was performed at a significantly faster frequency (M= 1.7 Hz) than muscular anti-phase coordination (M= 1.7 Hz, respectively). These findings indicate that the less stable the coordination pattern, the smaller the movement amplitude and the slower the movement frequency.

A main effect for Hand was marginally significant [F (1, 18) = 4.04, $p = .059$]. The observed trend suggests that the dominant, right hand moved at a slightly faster frequency than the non-dominant, left hand. These findings suggest that amplitude and frequency of movement were larger for the dominant right hand compared to the non-dominant left hand.

Two-factor interactions were found for Condition X Phase [F (1, 18) = 18.07, $p < .05$], Condition X Frequency [F (1, 18) = 10.78, $p < .05$] and Phase X Frequency [F (1, 18) = 27.32, $p < .05$]. Since a significant three-factor interaction between Condition, Phase and Frequency [F (1, 18) = 11.35, $p < .05$] was also observed only the latter effect will be described (Figure 6). Post hoc comparisons revealed that participants were able to perform muscular in-phase coordination at the requested frequencies during both compatibility conditions (compatible conditions, 1.5 Hz M= 1.5 Hz, and 2.0 Hz M= 2.0 Hz; incompatible conditions, 1.5 Hz M= 1.5 Hz and 2.0 Hz M= 2.0 Hz). However, participants were only able to perform muscular anti-phase coordination at the requested frequency during the compatible condition at 1.5 Hz (M= 1.5 Hz). For the 2.0 Hz compatible condition (M= 1.9 Hz) and for both frequencies for the incompatible condition (1.5 Hz M= 1.4 Hz and 2.0 Hz M= 1.7 Hz), participants were significantly slower than the target metronome pace for anti-phase coordination. Overall, participants were significantly slower than the target frequency during muscular anti-phase coordination for the incompatible condition at 2.0 Hz. This finding suggests that decreases in stability and accuracy of bimanual coordination associated with the incompatible condition resulted in significant decreases to movement frequency.

A three-factor interaction between Condition, Frequency and Hand was also significant [F (1, 18) = 5.4, $p < .05$]. This interaction suggests that participants moved both hands at the requested frequency for the compatible condition but were significantly slower during the incompatible condition regardless of pattern.

Involuntary switches: No trials met the predetermined criterion set for an involuntary transition.

Discussion

The purpose of this experiment was to determine whether the basis of bimanual coordination stability in healthy young adults is best explained by the widely accepted motoric view (Carson, et al., 2000; Kelso, 1984; Park et al., 2001; Swinnen, Jardin et al., 1997; Swinnen et al., 2000; Swinnen, Van Langendonk, et al., 1997) or the recently proposed perceptual view (Mechsner et al., 2001). If the motoric view is the basis of bimanual coordination, then it was expected that muscular activity would explain the stability of motor performance. That is, regardless of the visual information provided by the movement of the flags, muscular in-phase would be more stable than muscular anti-phase, particularly at the faster movement frequency. If the perceptual view is the basis of bimanual coordination, then it was expected that the visual information would explain the stability of motor coordination. That is, movement patterns performed with visual in-phase feedback would be more stable than movement patterns performed with visual anti-phase feedback, particularly at the faster frequency.

In general, all three measures of relative phase provided support for the *motoric* view of bimanual coordination. For both compatibility conditions both intrinsic patterns were performed with equivalent stability and accuracy at the slower movement frequency. While muscular in-phase coordination was performed with equal stability and accuracy for both movement frequencies, muscular anti-phase performance deteriorated at the faster movement frequency for both compatibility conditions. These findings support previous research in favour of a motoric view of bimanual coordination (Byblow et al., 1995; Kelso, 1984; Swinnen 2002; Swinnen et al., 1995). Results from the incompatible condition (in which the flags provided visual information that was opposite to the movement of the upper limbs) reveal that similar to the compatible condition, muscular in-phase was performed with greater stability and consistency than muscular anti-phase particularly at the faster movement frequency The results from the amplitude and frequency data also provide support for the motoric view. Results indicate that the more stable and accurate the coordination pattern, the closer performance was to the target amplitude and frequency For example, movement frequency and amplitude were closest to their respective targets for muscular in-phase coordination at the slower movement frequency during the compatible condition. Therefore, these findings suggest that muscular activation determines the stability of bimanual coordination rather than the visual perceptual qualities of the movement.

Although results in general support the motoric view, there was some evidence that visual perceptual information influences movement characteristics. An original premise of the present experiment based on Mechsner et al. (2001) was that if the perceptual view was correct, then the results would have indicated that when visual in-phase information was provided in the incompatible condition, the performance of muscular anti-phase would be stable and accurate. However, the opposite happened in that in this situation the performance became less stable and accurate (e.g., Figures 3 and 4). A further sign of instability was that movement frequency was significantly slower than the faster target frequency during performance of muscular anti-phase coordination with in-phase visual information (e.g., Figure 6). It might be argued that participants were unable to move at the faster frequency during the incompatible condition, however, participants were able to perform muscular in-phase at the faster frequency with visual anti-phase feedback.

It is possible that this instability could be explained as a response to an incompatible signal. But in this experiment, an incompatible signal of visual anti-phase information did not destabilize muscular in-phase performance. Chua and Weeks (1997) propose that the concepts of compatibility should be incorporated into dynamical systems theory to assess stability in coordination. That is, compatibility between the perceived movement direction and the movement of the upper limbs may be instrumental in determining the stability of motor behaviour (Buekers, Bogaerts, Swinnen, & Helson, 2000; Chua & Weeks, 1997). Indeed, the present findings show that when visual information provided by the flags was incompatible to the movements of the upper limbs, performance stability decreased for muscular anti-phase coordination. It may be possible that the powerful in-phase visual information was having an effect on the dynamics of the motor system by acting as an attractor that was destabilizing the motor pattern. From previous studies on bimanual coordination (Kelso, 1984; Scholz & Kelso, 1990), it is known that limb coordination tends to destabilize prior to a phase transition. It is possible that muscular anti-phase was destabilized as a result of the attraction of the in-phase visual information. In summary, on the surface, the experimental prediction based on Mechsner et al.'s work was not supported. But, nevertheless, there seems to be some support for the role of visual perceptual dominance in certain circumstances such as when the visual information is cueing in-phase and the motor system is somewhat destabilized, such as with the anti-phase pattern.

A possible reason why Mechsner et al. (2001) found strong support for the perceptual basis of bimanual coordination and the present experiment found only weak support may be because the perceptual view may be task specific. For example, in one experiment the finger task involved isolated abduction and adduction of the index fingers, which is motorically very challenging. The bimanual circle-drawing task dissociated the perceived movement of the flags from the movement of the upper limbs by having the right flag move at a faster frequency than the right hand. This was a complex task that took a considerable amount of practice to learn and consequently may not have examined the intrinsic coordination patterns per se. The perceptual view may be task specific and may not be generalized to other experimental paradigms.

A potential argument for why the present experiment did not have strong support for the perceptual view is that linear slide apparatus may not have adequately dissociated the visual information provided by the flags from the movement of the upper limbs. Considering it is impossible to completely dissociate proprioception from action a number of precautions were taken to increase participants' focus of attention to the visual feedback provided by the movement of the flags and thereby away from the movement of their upper limbs. For example participants were instructed and reminded throughout the experiment to 'concentrate on coordinating the flags in the correct pattern', no reference was made to the movements of the hands, and a cloth bib prevented participants from watching the movement of their arms. As well, visual indicators instead of physical stoppers marked the end points of the movement Nevertheless, the friction of the slides and the changing of directions at the end points of the linear movements may have increased participants' attention to the movement of the upper limbs. In addition, it should be noted that following each compatibility condition, participants stated that they concentrated on the movement of the flags for the 'majority' of each trial. However, there is no way to confirm empirically where participants focused their attention. Therefore, participants may have simultaneously concentrated on the visual information provided by the flags *and* the proprioceptive information from the upper limbs, instead of just the visual perceptual information, which may have been important in order to support the perceptual view.

The perceptual basis of bimanual coordination received minimal support in the present experiment. However, this view may be supported with a different task and with changes to the methodology. Although the prediction that visual in-phase information would improve the stability of muscular anti-phase was not supported when movements were performed in the horizontal plane (parallel to the frontal plane of the body), it may be supported when movements are performed in the vertical plane (orthogonal to the frontal plane of the body). Indeed, Bogaerts et al. (2002) found that in the vertical plane, performance with visual in-phase information was more stable than with visual anti-phase information and that muscular anti-phase performance is improved with visual in-phase feedback. Therefore, it appears that under certain task conditions, the perceptual qualities of the movement may dominate over muscular activity.

In addition to the possibility that the basis for bimanual coordination may vary depending on task, it is also possible that the attributes of the person may impact on how coordinated limb movements are generated. For example, the perceptual view may be supported with patient populations who are reliant on visual information to facilitate continuous movement performance, such as deafferented patients (Lajoie et al., 1992) and individuals with PD (Byblow et al., 2002; Cunnington, Iansek, Bradshaw, & Phillips, 1995). Deafferented patients who do not experience interference between proprioceptive and visual feedback are better able to adapt to visual information (e.g., mirror drawing task) that is incompatible with the actually generated movement than are healthy controls (Lajoie et al., 1992). Individuals with Parkinson's disease are more dependent on visual information provided by the environment than are healthy older adults. As a result, these patient populations are likely to be more stable with visual in-phase feedback than visual anti-phase feedback, lending for the perceptual view of bimanual coordination.

In summary, the findings from this experiment strongly support the widely accepted motoric view and provide only potential support for the perceptual view of bimanual coordination. In addition, these findings emphasize the importance of compatibility between upper limb coordination and visual feedback, particularly during muscular anti-phase coordination.

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Figure Captions

Figure 1: Illustration of apparatus

Figure 2: Illustration of compatible and incompatible conditions

Figure 3: RMSE of relative phase: Condition x Phase

Figure 4: RMSE of relative phase: Condition x Phase x Frequency

Figure 5: Amplitude: Phase x Frequency x Hand

Figure 6: Frequency: Condition x Phase x Frequency

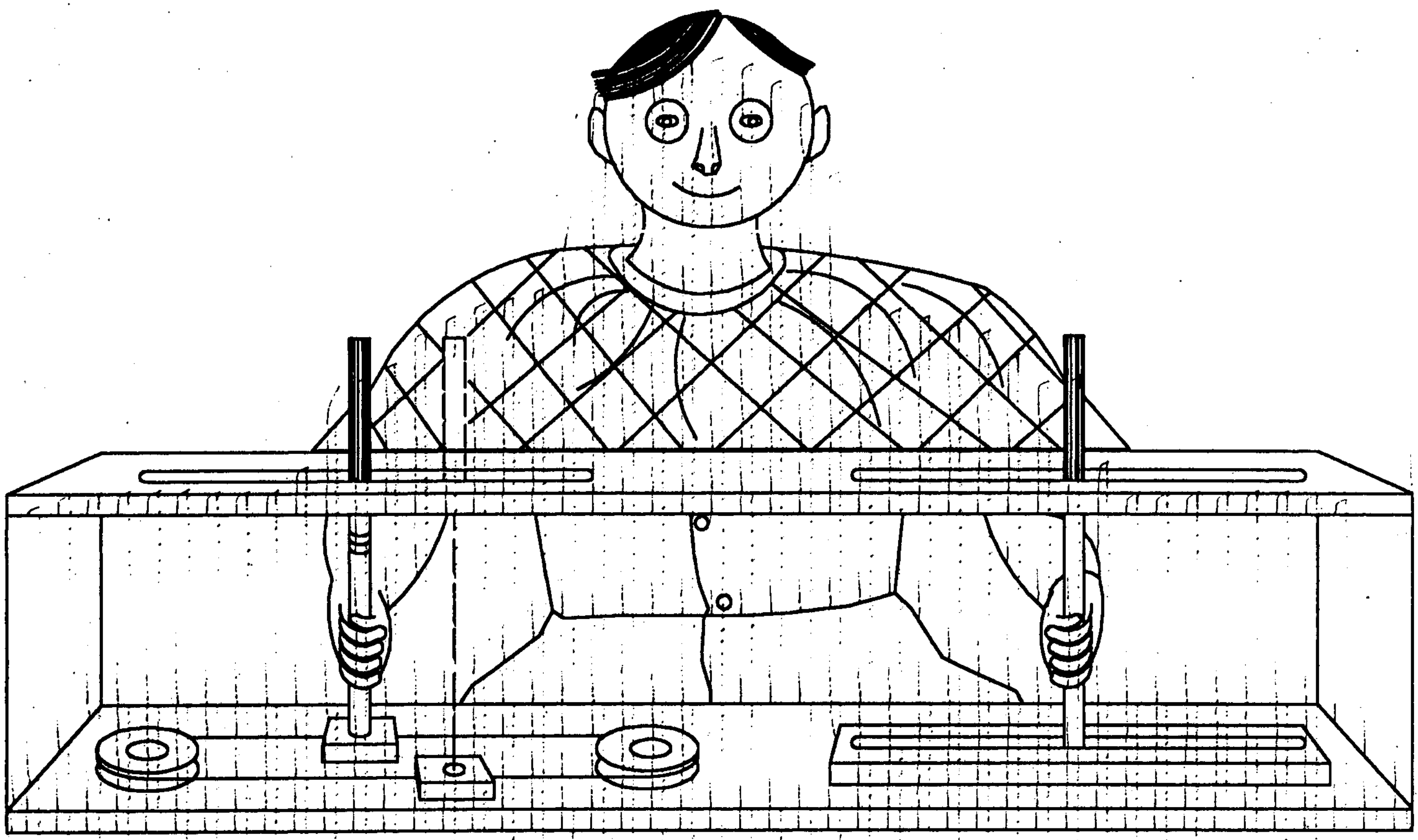
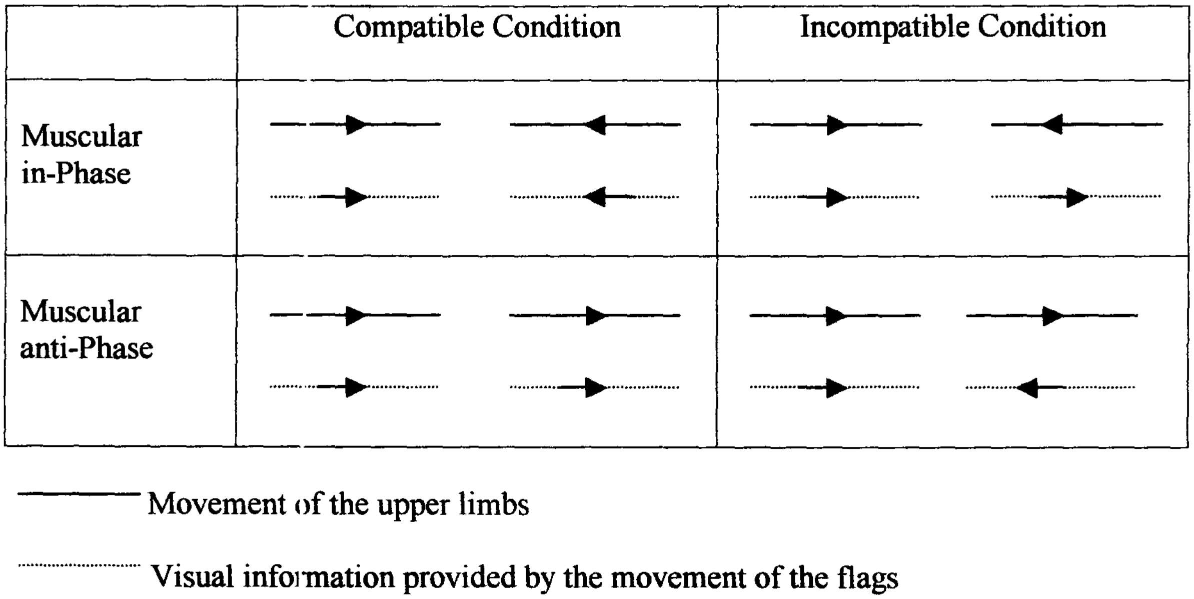


Figure 1. Illustration of apparatus. Participant is wearing a cloth bib to block vision of their upper limbs. Hatched flag indicating set up for the incompatible condition.

Figure 2. Illustration of compatible and incompatible conditions



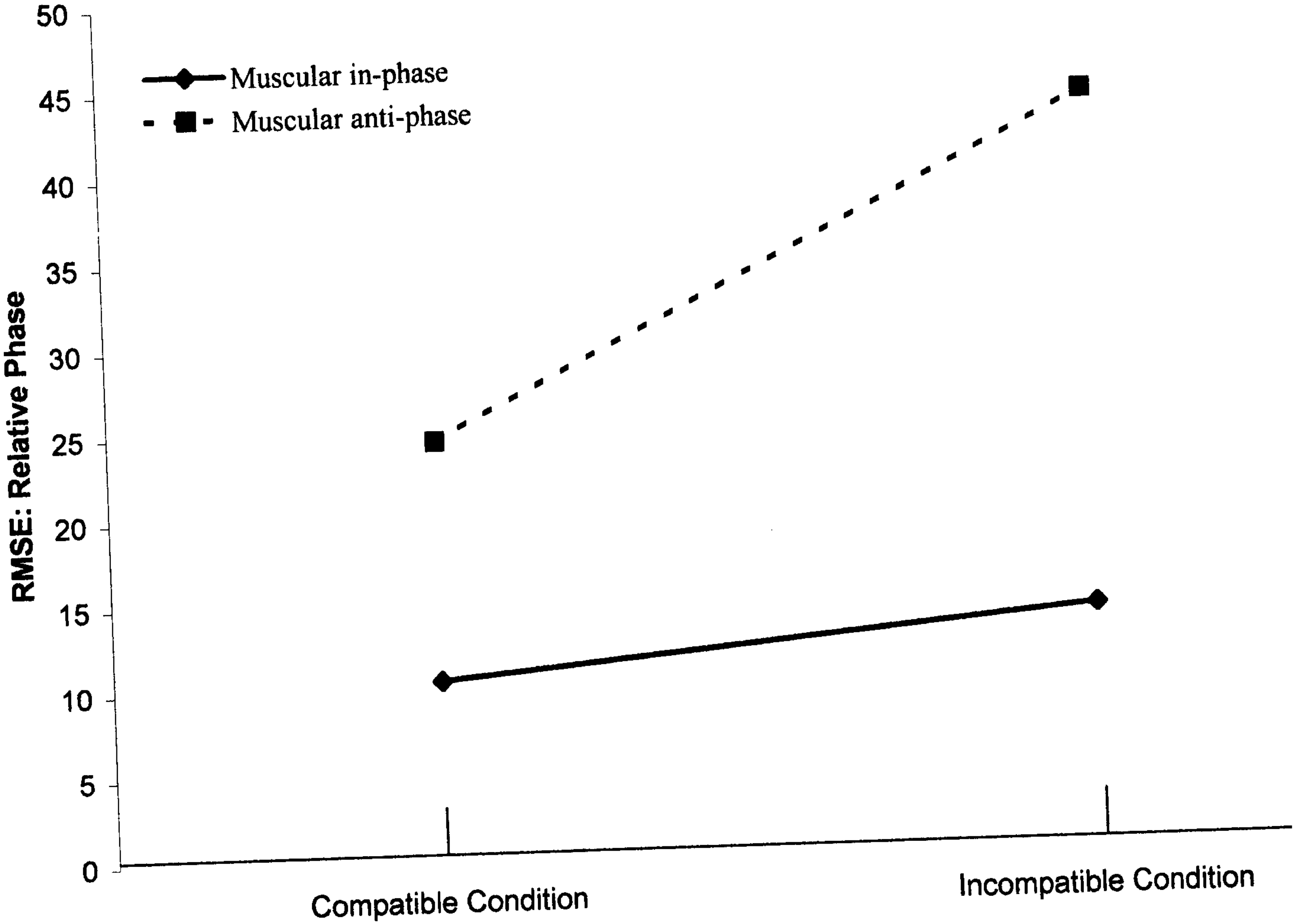


Figure 3: RMSE: Condition x Phase [$F(1, 18) = 43.46$, $p < .05$]

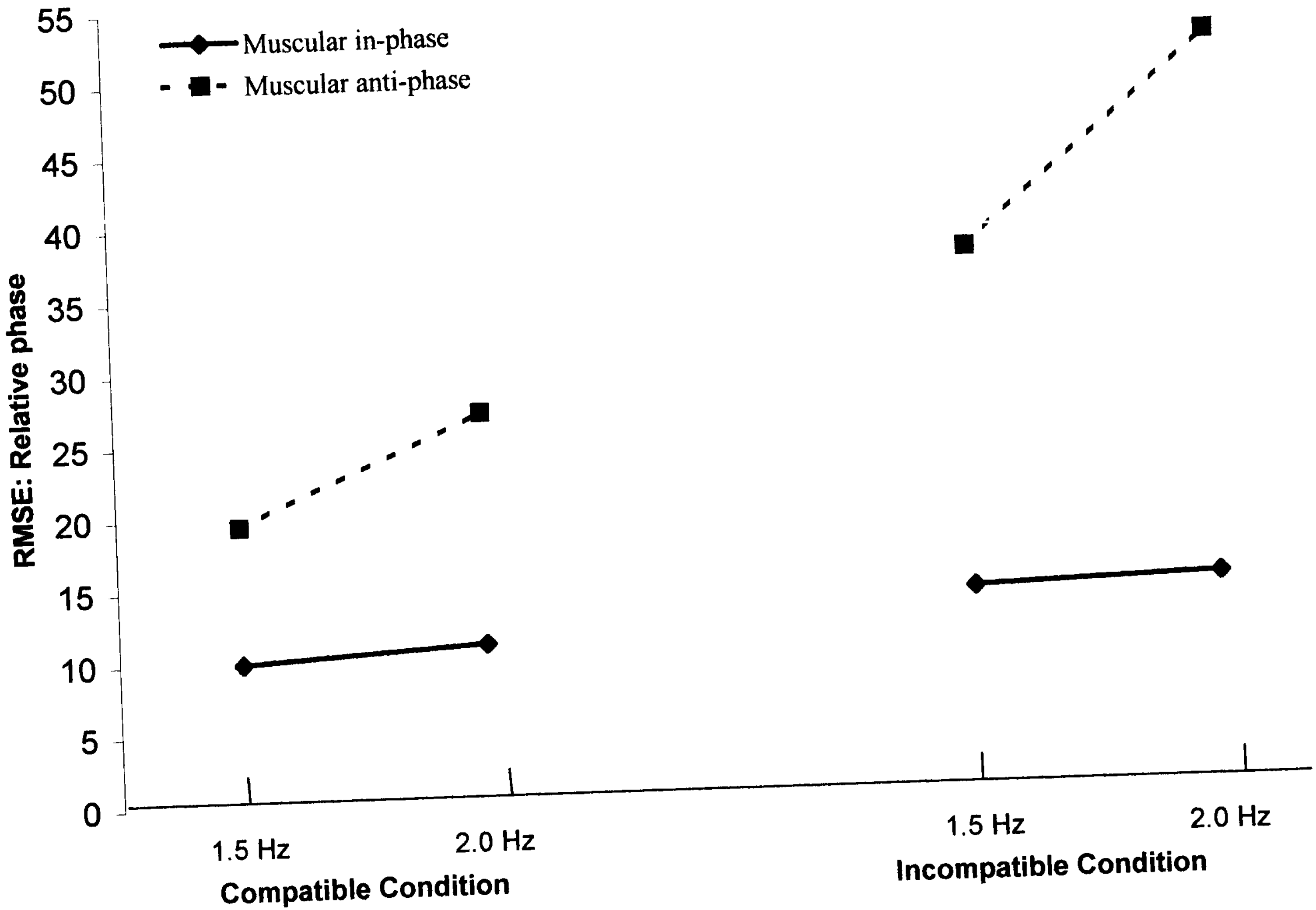


Figure 4: RMSE: Condition x Phase x Frequency [$F_{(1,18)} = 4.07$, $p < .05$]

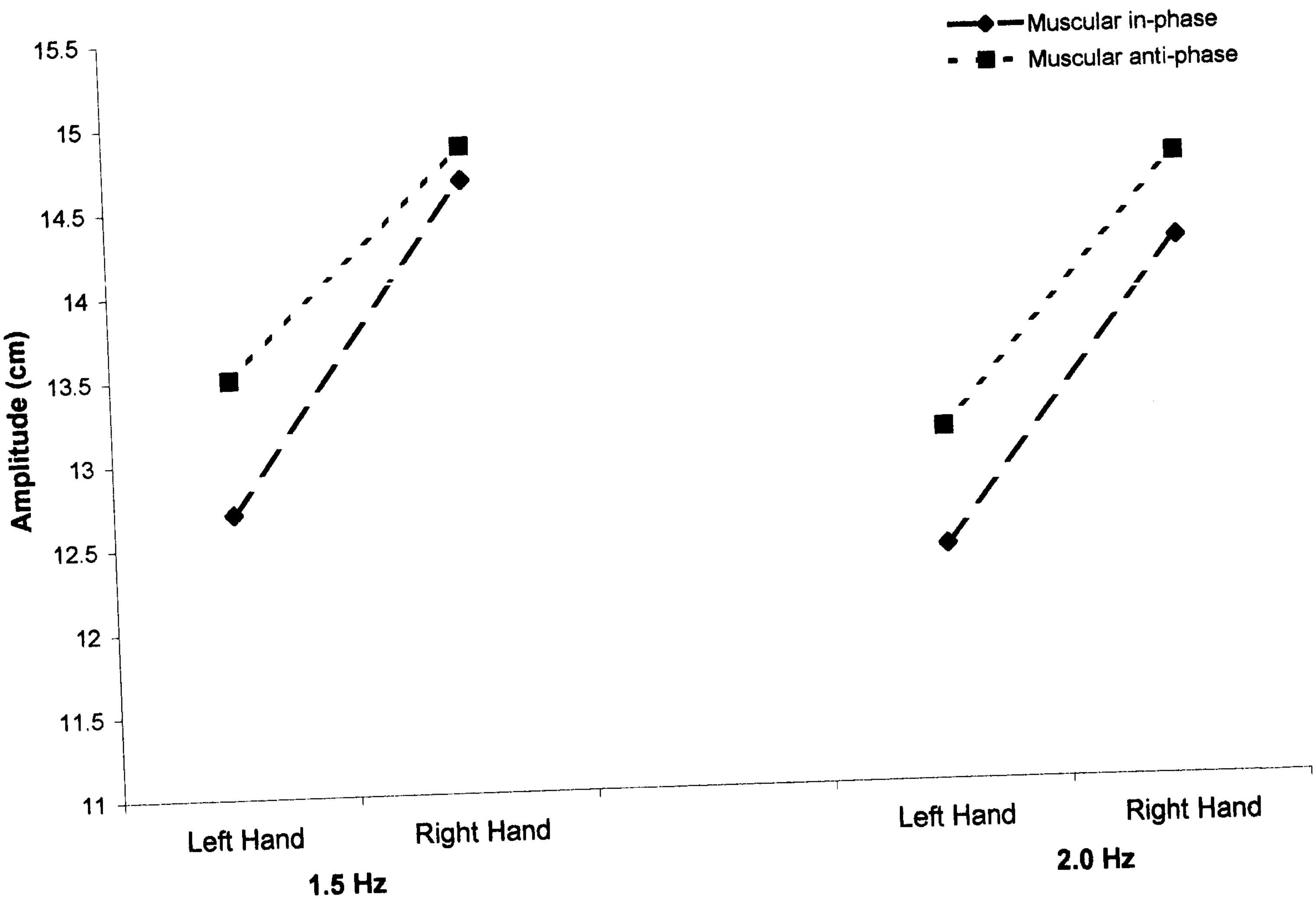


Figure 5: Amplitude: Phase x Frequency x Hand [$F(1,18)=4.5$, $p < .05$]

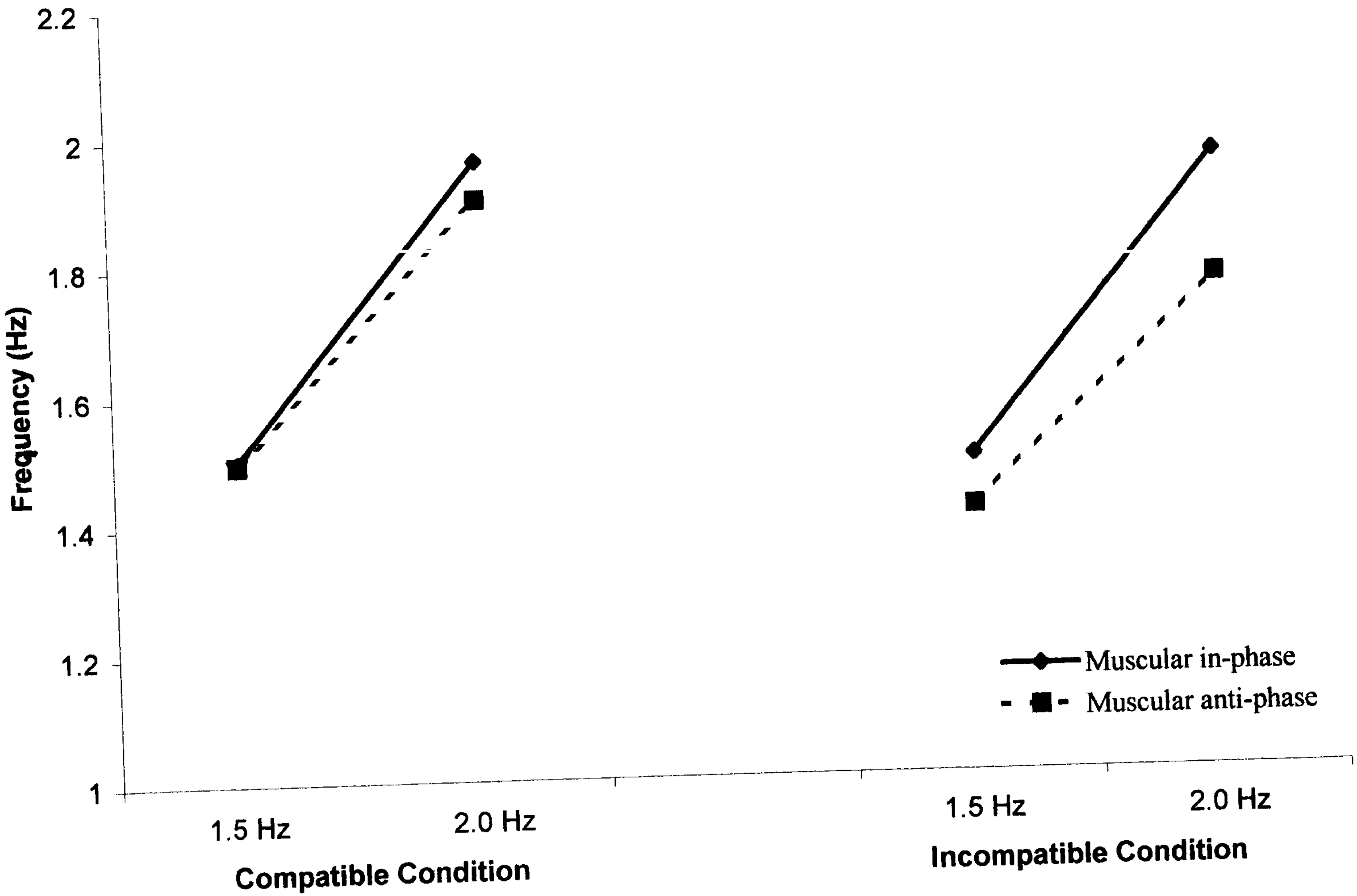


Figure 6: Frequency: Condition x Phase x Frequency [$F(1,18)=11.35$, $p < .05$]

The Basis of Bimanual Coordination in Individuals with Parkinson's disease: The Perceptual versus Motoric View

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Abstract

Currently, controversy in the literature exists as to whether the basis of stability of bimanual coordination is perceptual or motoric. That is, are intrinsic patterns stable due to muscular activity or due to the perceptual qualities of the movement. Considering individuals with PD are dependent on visual information to facilitate movement production, it was predicted that the perceptual view might be favoured more in this population than in a group of age- and sex- matched controls. Nine right-handed individuals with PD (M age= 71.78, stage 2-4 on the Hoehn and Yahr scale) and 9 right handed healthy age- and sex- matched controls (M age= 70.78) performed continuous horizontal and linear movements at 1.0 and 1.5 Hz. The goal of the task was to coordinate two flags visually in-phase or visually anti-phase by coordinating the upper limbs in in-phase or anti-phase. In a compatible condition, the perceived movement direction of the flags (e.g., visual in-phase) corresponded to the movement of the upper limbs (e.g., muscular in-phase). In an incompatible condition, the visual information provided by the flags (e.g., visual in-phase) was opposite to the movement of the upper limbs (e.g., muscular anti-phase). Contrary to predictions, measures of relative phase accuracy and stability revealed that the motoric view of bimanual coordination was supported in both the individuals with PD and in the healthy controls. Muscular in-phase *and* muscular anti-phase coordination destabilized with incompatible visual feedback. Therefore, the findings strongly support the motoric basis of bimanual coordination stability in individuals with PD. Furthermore these findings emphasize the importance of

compatibility between upper limb movements and visual feedback to ensure stability of the intrinsic coordination patterns for individuals with PD.

The Basis of Bimanual Coordination in Individuals with Parkinson's disease: The Perceptual versus Motoric View

The majority of daily activities require the integrated performance of the upper limbs. Activities such as tying shoelaces, washing hair, dressing, or preparing a meal, all require the hands and arms to work together, coordinating their movements so that the goals of the task are achieved. With age and the onset of disease maintenance of the ability to perform coordinated tasks with the upper limbs is an essential component to remain independent. However, individuals with Parkinson's disease (PD) exhibit decrements in their ability to perform coordinated movements with the upper limbs (e.g., Almeida, Wishart, & Lee, 2002; Johnson, Cunnington, Bradshaw, Phillips, Iansek, & Rogers, 1998). As the disease progresses, these individuals are at risk for becoming more dependent and may eventually require continual care.

The rationale for this experiment is to provide a further understanding of the mechanisms of the upper limb coordination deficits associated with PD. The identification of the mechanisms underlying the specific motor control deficits associated with PD is the first step in developing rehabilitation programs to improve/maintain coordinated movement.

Upper limb coordination literature suggests that the human motor control system possesses an intrinsic tendency to perform two modes of bimanual coordination, called in-phase and anti-phase coordination (Kelso, 1984; Schöner & Kelso, 1988; Turvey, 1990; Yamanishi, Kawato, & Suzuki, 1980). During continuous movements of both upper limbs in the horizontal plane, in-phase coordination refers to symmetrical movements made towards and away from the longitudinal axis of the body, whereas anti-phase coordination refers to movements made in the same direction from one side of the longitudinal axis of the body to the other. In healthy young adults, in-phase coordination is performed with greater accuracy and consistency than anti-phase movements, especially at faster movement frequencies (Byblow, Chua & Goodman, 1995; Kelso, 1984; Lee, Blandin, & Proteau, 1996; Riek, Carson & Byblow, 1992). Compared to healthy young adults, older adults are as accurate and stable during in-phase coordination but perform anti-phase movements with greater mean error and variability, particularly at movement frequencies faster than preferred (Greene & Williams, 1996; Salter, Wishart, & Lee, 2001; Wishart, Lee, Cunnington, & Murdoch, 2002; Wishart, Lee, Murdoch, & Hodges, 2000)

The decreased stability of upper limb coordination of individuals with PD becomes apparent when these individuals perform the patterns at frequencies faster then preferred, when they attempt to switch from one pattern to another, or when they try to learn a new coordination pattern. Compared to older adults, individuals with PD are as accurate and stable in their performance of in-phase coordination but perform anti-phase coordination with greater mean error and variability, particularly at frequencies faster than preferred (Almeida et al., 2002; Geuze, 2001; Johnson et al., 1998; van den Berg, Beek, Wagenaar, & van Wieringen, 2000). In general, coordinated movements are performed more slowly (bradykinesia) (Morris, 2000) and involuntary transitions from anti-phase to in-phase coordination occur at significantly lower movement frequencies compared to those of healthy older adults (Byblow, Summers, Lewis, & Thomas, 2002).

Individuals with PD take significantly longer to voluntarily switch between coordination patterns, exhibiting greater difficulty switching from in-phase to anti-phase coordination than vice versa (Almeida, 1999). Individuals with PD also perform coordinated movements with smaller amplitudes (hypometria) (Byblow et al., 2002; Swinnen, Van Langendonk, Verschueren, Peeters, Dom, & de Weerdt, 1997). Individuals with PD are able to learn new coordination patterns with the upper limbs, but they never reach the performance levels of healthy older adults (Swinnen, Steyvers, Van Den Bergh, & Stelmach, 2000).

Despite the fact that anti-phase performance deteriorates with age and with PD, in-phase and anti-phase coordination still remain more stable than all other phase relations. Currently in the literature there exists controversy as to why this is so. The predominant motoric view suggests that the mechanisms of bimanual coordination are explained by muscular activity (Carson, Byblow, Abernethy, & Summers, 1996; Johnson, et al., 1998; Kelso, 1984; Park, Collins, & Turvey, 2001; Swinnen, Jardin, Meulenbroek, Dounskaia, & Hofkens-Van Den Brandt, 1997). This view suggests that in-phase performance is more stable and more accurate than other coordination patterns because homologous muscle groups are activated simultaneously (muscular in-phase), whereas anti-phase coordination is more variable because non-homologous muscle groups are activated simultaneously (muscular anti-phase).

This motoric view has recently been challenged based on research by Mechsner and colleagues (Mechsner, Kerzel, Knoblich, & Prinz, 2001). They propose that the visual perceptual qualities of movement dominate over the muscular activity required to perform the movement. Specifically, movements that are visually perceived to be symmetrical are preferred over alternate coordination tendencies, regardless of the movement of the limbs producing the movement. This view suggests that in-phase performance is the more stable and more accurate than other coordination patterns because it is visually perceived to be symmetrical (visual in-phase), whereas anti-phase coordination is more variable because it is visually perceived to be asymmetrical (visual anti-phase).

A previous study conducted in our lab (Salter, Wishart, Lee, & Simon, 2002), examined the motoric versus perceptual views of the basis of bimanual coordination in healthy young adults. The goal of the task was to coordinate two flags in in-phase (visual in-phase) or anti-phase (visual anti-phase) by continuously moving the upper limbs linearly and horizontally in in-phase (muscular in-phase) or anti-phase (muscular anti-phase) coordination. A comparison of the motoric versus perceptual view was based on the relationship between the movement of the flags and the movement of the upper limbs. The flags could be attached to the apparatus to become compatible or incompatible to the movement of the upper limbs. In the compatible condition, the visual information provided by the movement of the flags corresponded with the movement of the upper limbs (e.g., muscular in-phase corresponded with visual in-phase and muscular anti-phase corresponded with visual anti-phase). In the incompatible condition, a 180- degree transformation between the right flag and right hand dissociated the visually perceived movement direction from the movement of the upper limbs (i.e., muscular in-phase corresponded with visual anti-phase and muscular anti-phase corresponded with visual in-phase). These coordination patterns were externally paced at a slow (1.5 Hz) and fast (2.0 Hz) movement frequency. Results indicated that regardless of the movement of the flags, muscular in-phase was more stable than muscular anti-phase. In addition, muscular anti-phase destabilized while muscular in-phase remained stable with incompatible visual information. Although results in general supported the motoric view, there was some evidence that visual perceptual information influenced the movement characteristics. The results from this study and from Mechsner et al. (2001) support the idea that the basis of bimanual coordination is dependent on the task constraints and the motor control abilities of the individual.

It has been well documented that individuals with PD are extremely reliant on visual information to facilitate continuous movement performance (Byblow, et al., 2002; Cunnington, Iansek, Bradshaw, & Phillips, 1995; Iansek, Bradshaw, Phillips, Cunnington, & Morris, 1995; Kritikos, Leahy, Bradshaw, Iansek, Phillips, & Bradshaw, 1995; Morris, 2000; Praamstra, Stegeman, Cools, & Horstink, 1998). For example, external visual cues such as lined paper have improved hypometric handwriting (Oliveira, Gurd, Nixon, Marshall, & Passingham, 1997), white lines placed on the floor perpendicular to the direction of movement have improved gait velocity and stride length (Dietz, Goetz, & Stebbins, 1990; Martin, 1967), and visual information about performance significantly improved learning of a new bimanual coordination pattern (Verschueren, Swinnen, Dom, & Weerdt, 1997). Visual information also provides a strategy to compensate for a PD-related decline in proprioception (Demirci, Grill, McShane, & Hallett, 1996; Schneider, 1991; Schneider, Diamond, & Markham, 1987;

Swinnen et al., 2000). Given that individuals with PD are reliant on visual information for many types of movement tasks, the perceptual view may be the basis of bimanual coordination characteristics for this patient population. An understanding of the basis of bimanual coordination in PD (whether motoric or perceptual) will increase the understanding of PD, which in turn will aid in the development of rehabilitative interventions.

The purpose of this experiment was to determine whether the characteristics of bimanual coordination in individuals with PD are best explained by the widely accepted motoric view or the recently proposed perceptual view. The methodology was similar to that used by Salter et al. (2002) with the exception that the boundary markers between which the flags were to move were made more salient and movements were externally paced at a slow (1.0 Hz) and a fast (1.5 Hz) movement frequency (instead of at 1.5 and 2.0 Hz). These movement frequencies were chosen based on pilot testing which revealed that healthy older adults and individuals with PD were unable to perform the incompatible condition trials at frequencies faster than 1.5 Hz. The 1.5 Hz movement frequency was chosen to allow for the possibility of comparison of performance between the healthy young adults from Salter et al. (2001) and the participants from the present experiment.

In general, it was predicted that regardless of the compatibility condition, coordination performance of the individuals with PD would be less accurate, less stable, and produced with a smaller amplitude (hypometria) and slower movement frequency (bradykinesia), particularly at the 1.5 Hz trials, compared to healthy older adults.

It was predicted that if the motoric view is the basis of bimanual coordination for individuals with PD, then regardless of the perceived movement direction of the flags, muscular in-phase would be more stable and more accurate than muscular anti-phase. In addition, muscular in-phase would remain stable with increasing movement frequency and involuntary transitions away from muscular anti-phase would occur. In contrast, if the perceptual view is the basis of bimanual coordination for individuals with PD, then regardless of the movement of the hands, visual in-phase would be more stable and more accurate than visual anti-phase. Specifically, visual in-phase would remain stable with increasing movement frequency, and involuntary transitions away from visual anti-phase would be evident. Consequently, it was anticipated that muscular anti-phase performance would benefit from visual feedback that was visually in-phase.

Based on the findings from Salter et al. (2002), it was predicted that muscular in-phase would be equally stable and accurate for both compatibility conditions. However, because individuals with PD are dependent on visual information, it was predicted that muscular anti-phase would destabilize with visual in-phase information, even more than it does for healthy older adults.

Methods

Participants

Nine (5 female, 4 male) individuals diagnosed with idiopathic PD (M age=71.78 years, range=57-85) and nine age- and sex- matched healthy older adults (M age=70.78 years, range=57-88) participated in this experiment. Individuals with PD were recruited from a rehabilitation program in Hamilton, Ontario. Healthy older adults were spouses of the individuals with PD or volunteers at a continuing care hospital located in Hamilton, Ontario. All participants were community dwelling and independently functioning. Participants were excluded if they had neurological disturbances (other than PD in the experimental group), cognitive impairment (below 23 on the Mini Mental Status Examination), (Folstein, Folstein, & McHugh, 1975), hearing loss, visual impairment, or suffered from upper limb problems such as arthritis. No participants had previous experience with the task. In addition, individuals with PD were excluded if they had a Hoehn and Yahr score greater than 3 (Hoehn & Yahr, 1967). From an initial sample of 11 participants with PD, two were excluded from analysis because they were unable to coordinate the flags in the correct phase relationship following the practice session.

All participants read and signed a consent form prior to testing and received an honorarium of $10.00 (Cdn). Upon completing the experiment, participants were debriefed and thanked. This experiment received ethical approval from the Research Ethics Board at McMaster University and the Research Committee at St. Peter's Hospital.

All participants were right-handed (PD, M=24.11 range=21-27, control M=26, range=25-27), as determined by the Waterloo Handedness Questionnaire (Bryden, 1977) (Appendix). General measures of motor control and cognitive functioning were collected to ensure that participants were representative of their age-group norms. The following tests were performed on all participants (Table 1): the Mini-Mental Status Examination (MMSE) (Folstein, et al., 1975) was used as a screening tool for mental status (minimum acceptable score 23) (Appendix), the Physical Activity Scale for the Elderly (PASE)

(Washburn, Smith, Jette & Janney, 1993) was used to determine levels of physical activity and health and The Minnesota Manual Dexterity Turning test (MMDT) (American Guidance Services, 1969; Lafayette Instrument Company) provided a general measure of manual dexterity. Performance on the MMDT for both participant groups was compared to established reference values for older adults (Desrosiers, Rochette, Herbert, & Bravo, 1997). Individuals with PD were additionally assessed on the Unified Parkinson's Disease Rating Scale (UPDRS) (Fahn & Elton, 1987) to determine the severity of symptoms and the Modified Hoehn and Yahr Staging scale (Hoehn & Yahr, 1967) to determine the overall severity of PD (Appendix). The healthy older adults scored within the age-expected norms on each of these measures. The individuals with PD were within the age-expected norms for the MMSE and the PASE but were significantly slower than the age-expected norms for the MMDT. Indicative of bradykinesia, the individuals with PD took on average approximately twice as long to complete the MMDT. Two individuals with PD and their age- and sex- matched controls completed the MMDT but they could not be scored on the PASE as the questionnaire only provides norms for participants over 65 years of age.

All participants with PD were taking levodopa, with or without other medication and their medication schedules were stable. The last dose of levodopa was taken 0.5 hours before the experiment and demographic information was collected for the first half hour. This timetable ensured that the bimanual coordination task was performed a minimum of one hour following medication administration, during the 'on' stage of the medication cycle.

The duration of PD ranged from 3 to 30 years (M= 8.67 years). The severity of PD was rated at stage 2 to 3 according to the Hoehn and Yahr Scale (Hoehn & Yahr, 1967) (Table 1). On the UPDRS, the mean subscore was 3.5 (range, 2-6) on section I (mentation, behaviour and mood), 18.6 (range, 9-29.5) on section II (activities of daily living), and 37.7 (range=26-51) on section III (motor examination). The maximum possible subscore for each of these sections is 16, 52, and 56, respectively, with higher scores reflecting greater impairment. Three individuals with PD were most affected on the left side of the body, 2 on the right side of the body and 4 were equally affected on each side of the body.

Apparatus and Task

The apparatus and task were similar to those described in Salter et al., (2002) with the exception black flags were added at the 'in' and 'out' boundary markers and movements were externally paced at 1.0 Hz and 1.5 Hz. Specifically, two 16 cm regions, directly in front of the flags, marked the boundaries between which the flags were to be moved. The points closest to the body midline were referred to as the "in" positions and the maximum lateral points were referred to as the "out" positions. The black flags (1.5 cm wide, 9.5 cm high) extended vertically from the distal edge of the wood platform at the "in" and "out" positions. Participants were instructed to move the yellow flags behind the black flags before switching direction. This modification to the apparatus from Salter et al. (2002) was added in an attempt to further draw participants' attention to the visual feedback provided by the movement of the yellow flags.

Procedure

The procedure was similar to the procedure followed by Salter et al., (2002) with the exception that movements were externally paced at 1.0 and 1.5 Hz (instead of 1.5 and 2.0 Hz), and all participants performed all the trials for the incompatible condition followed by all the trials for the compatible condition. The frequency of movement was decided upon based on previous experiments (Almeida, et al., 2002; Byblow et al., 2002; Geuze, 2001; Johnson et al., 1998) and pilot testing with the healthy older adults. In pilot testing at frequencies faster then 1.5 Hz, participants had difficulty performing the incompatible condition trials.

The length of each trial was 20 s and the inter-trial interval was approximately 20 s. The total duration of the experiment, including instructions and collection of demographic information and motor characteristics, was approximately 90 minutes for the individuals with PD and 60 minutes for the healthy age- and sex-matched controls.

All participants who were included into the statistical analyses were able to perform the requested pattern following practice.

Although it was expected that the compatible condition would yield results similar to previous findings with older adults and individuals with PD (i.e., Greene & Williams, 1996; Johnson et al., 1998; Wishart et al., 2000), it was necessary to include this condition to ensure that in-phase and anti-phase coordination could be reproduced with the present experimental set-up. In the previous experiment by Salter et al. (2002), it was anticipated that the order of the compatibility conditions would influence performance. However, statistical analyses did not reveal a main effect for Order suggesting that the incompatible condition did not affect the ability to perform the compatible condition and vice versa. As a result, all participants in the present experiment performed the incompatible condition followed by the compatible condition.

As with Salter et al., (2002) participants performed 16 incompatible condition trials followed by 16 compatible condition trials, for a total of 32 trials. Within each compatibility condition, bimanual coordination patterns were counterbalanced for order (ABBA BAAB). A 1.0 Hz trial was always followed by a 1.5 Hz trial of the same coordination pattern. Therefore, for each compatibility condition, four trials were collected for each coordination pattern at each frequency. The healthy older adults were scheduled a 15 min rest between compatibility conditions, at which point they completed the PASE. Individuals with PD were scheduled a half hour rest between compatibility conditions, at which point the experimenter conducted the UPDRS. During this time and unbeknown to the participants, the right flag was removed from the chain and pulley system and reattached to the slide carriage for the compatible condition.

Data Analyses

Data analyses was the same as for Salter et al., (2002). Statistical analyses were performed using analyses of variance (ANOVA). All ANOVA's were mixed designs, with Group (Parkinson's disease, healthy controls) as the between-group factor and all other variables as within-group factors. Relative phase was analyzed in a 2 Condition (compatible, incompatible) X 2 Phase (muscular in-phase, muscular anti-phase) X 2

Frequency (1.0, 1.5 Hz) ANOVA. Frequency and amplitude of movement was analyzed using a 2 Condition (compatible, incompatible) X 2 Phase (muscular in-phase, muscular anti-phase) X 2 Frequency (1.0, 1.5 Hz) X 2 Hand (left, right) mixed design. Tukey's HSD post hoc comparisons were performed on all significant effects and interactions. For all tests alpha was set at .05.

It was hypothesized that main effects for Group for all dependent measures would be obtained, showing that individuals with PD are less stable and less accurate, perform with smaller amplitudes, and are slower than the healthy older adults. If the motoric view is the basis of bimanual coordination, then it was hypothesized there would be a main effect for Phase, showing that muscular in-phase is more stable and accurate than muscular anti-phase. A main effect for Condition was not expected. It was hypothesized that there would also be two-way interactions between Group and Frequency, with individuals with PD being less stable and less accurate at the faster frequency, between Group x Phase interaction, with individual with PD being less stable and accurate during muscular anti-phase and between Phase and Frequency, with muscular anti-phase becoming less stable and accurate at the faster frequency. If the perceptual view is the basis of bimanual coordination then it was hypothesized that there would be a three-way interaction between condition, phase and frequency, in which during the compatible condition, muscular in-phase would be more stable than muscular anti-phase, but during the incompatible condition, muscular anti-phase would be more stable than muscular in-phase.

Results

Relative phase accuracy: Statistical analysis of the absolute mean error of relative phase (accuracy) revealed a significant main effect for Group [F (1, 16) = 4.54, $p < .05$]. The individuals with PD (M= 29.8°) were not as accurate as the healthy age- and sex-matched controls (M= 19.7°). Main effects for Condition [F (1, 16) = 15.82, $p < .05$], Phase [F (1, 16) = 12.15, $p < .05$], and Frequency [F (1, 16) = 17.21, $p < .05$] were also obtained. Participants were significantly more accurate for the compatible (M= 18.1°) than the incompatible condition (M= 31.4°), with muscular in-phase (M= 15.7°) than muscular anti-phase (M= 33.8°) and with the slower (M= 20.7°) than the faster (M= 28.9°) movement frequency.

Figure 3 illustrates the significant two-way interaction between Phase and Frequency [F (1, 16) = 9.59, $p < .05$]. Post hoc comparisons confirmed that the difference between relative phase accuracy for the 1.0 and 1.5 Hz trials was negligible for muscular in-phase (M= 14.7° and 16.7°, respectively) whereas, muscular anti-phase coordination was significantly less accurate at 1.5 Hz (M= 40.9°) than at 1.0 Hz (M= 26.7°).

There were no significant interactions involving Group, specifically with Condition. The lack of a Group x Condition interaction suggests that differences in between the individuals with PD and the healthy older adults were similar for both compatibility conditions. Although there were no significant interactions with compatibility condition, a three-way interaction between condition, phase, and frequency approached significance [F (1, 16) = 3.68, p = .07] and may have been significant with a larger sample size. Figure 4 demonstrates that regardless of the compatibility condition, muscular in-phase tended to be more accurate than muscular anti-phase. Muscular in-phase was performed with equivalent accuracy for both movement frequencies (compatible conditions, 1.0 Hz M= 9.9° and 1.5 Hz M= 12.4°; incompatible conditions, 1.0 Hz M=19.5° and 1.5 Hz M=20.9°). The accuracy of muscular anti-phase decreased at the faster movement frequency, particularly for the incompatible condition (compatible conditions, 1.0 Hz M= 20.8° and 1.5 Hz M= 29.5°; incompatible conditions, 1.0 Hz M=32.6° and 1.5 Hz M=52.6°). In addition, the data suggests that during the incompatible condition, muscular in-phase was performed with similar accuracy compared to muscular anti-phase during the compatible condition.

Relative phase standard deviation: Statistical analysis of the standard deviation of relative phase (stability) revealed main effects for Group [F (1, 16) = 8.41, $p < .05$], Condition [F (1, 16) = 39.32, $p < .05$], and Phase [F (1, 16) = 25.54, $p < .05$]. Individuals with PD (M= 21.34°) were significantly more variable in their coordinated movements than the healthy controls (M= 14.4°). All participants were significantly less stable during the incompatible (M= 23.0°) than the compatible condition (M= 12.7°) and with muscular anti-phase (M= 23.9°) than with muscular in-phase coordination (M= 11.8°). A main effect for Frequency was marginally significant [F (1, 16) = 3.44, $p > .05$] (1.0 Hz M= 16.8°, 1.5 Hz M= 18.9°).

Figure 5 illustrates the two-way interaction between Group and Phase [F (1, 16) = 5.22, $p < .05$]. Post hoc comparisons confirmed that muscular in-phase coordination was performed with equivalent stability for both participants groups (controls M= 11.0°; PD

M= 12.5°) but that the individuals with PD performed muscular anti-phase with significantly less stability (M= 30.2°) than were the healthy older adults (M= 17.7°).

Although there were no significant interactions with compatibility condition, a two-way interaction between Condition and Phase approached conventional levels of significance, suggesting that with a larger sample size statistical significance would be obtained [$F(1, 16) = 3.59$, $p = .07$] (Figure 6). Results suggest that there is a tendency for both muscular in-phase (compatible condition M= 7.7° and incompatible condition M= M= 15.8°) and muscular anti-phase (compatible condition M= 17.6° and incompatible condition M= 30.3°) to destabilize with incompatible visual information.

Root Mean Square of Relative Phase: Analysis of overall relative phase performance error (RMSE) revealed main effects for Group [$F(1, 16) = 5.57$, $p < .05$], Condition [$F(1, 16) = 21.83$, $p < .05$], Phase [$F(1, 16) = 15.39$, $p < .05$], and Frequency [$F(1, 16) = 15.20$, $p < .05$]. The individuals with PD performed with significantly greater error (M= 37.1°) than the healthy older adults (M= 24.7°). Greater performance error was associated with the incompatible (M= 39.5°) compared to the compatible condition (M= 22.3°), with muscular anti-phase (M= 41.9°) compared to muscular in-phase (M= 19.8°), and with the faster (M= 34.9°) compared to the slower (M= 26.8°) movement frequency.

A two-way interaction between Phase and Frequency [$F(1, 16) = 8.75$, $p < .05$] was significant. Post hoc comparisons confirmed that while there was a negligible difference between performance error for muscular in-phase at both frequencies (1.0 Hz M= 18.7° and 1.5 Hz M= 20.9°), muscular anti-phase was performed with significantly greater error for the 1.5 Hz (M= 48.9°) compared to the 1.0 Hz (M= 34.9°) frequency trials.

Although there were no significant interactions with Group a two-way interaction between Group and Phase approached significance [F (1, 16) = 3.52, p = .07]. The data suggest that muscular in-phase coordination was performed equally well for both participant groups (controls M= 18.9°, PD M= 20.7°) but that the individuals with PD performed muscular anti-phase with greater error (M= 53.4°) than did the healthy older adults (M= 30.5°).

Amplitude: The target amplitude was 16 cm for the right and left hands. Statistical analysis of observed movement amplitude revealed a main effect for Group [F (1, 16) = 6.29 p < .05]. This effect showed that the amplitude of movement was significantly larger for the healthy older adults (M= 16.5 cm) compared to the individuals with PD (M= 13.9 cm). A main effect for Frequency [F (1, 16) = 5.28, p < .05] indicated that an increase in movement frequency was associated with a significant decrease in movement amplitude (1.0 Hz M= 15.4 cm and 1.5 Hz M= 15.0 cm)

Significantly larger amplitudes were produced during the incompatible condition than during the compatible condition. This was evident in significant interactions between Condition and Phase [F (1, 16) = 7.35, p < .05], Condition, Phase and Hand [F (1, 16) = 6.03, p < .05] (Figure 7), and Condition, Phase, Frequency and Hand [F (1, 16) = 14.02, p < .05].

Significantly larger amplitudes were observed for the dominant right hand (M= 16.3 cm) compared to the non-dominant left hand (M= 14.4 cm) [F (1, 16) = 3.65, $p < .05$]. This result was confirmed by significant two-way interactions for Phase and Hand [F (1, 16) = 7.34, $p < .05$] and Frequency and Hand [F (1, 16) = 7.55, $p < .05$] and a marginally significant three-way interaction between Phase, Frequency, and Hand [F (1, 16) = 8.75, $p = .054$]. Post hoc comparisons confirmed that the amplitude of movement of the right hand was significantly larger than the left hand for both coordination patterns and at both movement frequencies.

Frequency: The target frequencies were 1.0 Hz (slow) and 1.5 Hz (fast). Significant main effects for Condition [F (1, 16) = 6.46 $p < .05$] and Phase [F (1, 16) = 9.2, $p < .05$] indicated that movement frequency was significantly faster during the compatible (M= 1.2 Hz) than during the incompatible condition (M= 1.0 Hz) and for muscular in-phase (M= 1.1 Hz) than for muscular anti-phase coordination (M= 1.0 Hz). These findings suggest that the more stable the coordination pattern or compatibility condition, the faster the frequency of movement. A main effect for Frequency confirmed that the 1.0 Hz trials were significantly slower (M= 0.96 Hz) than the 1.5 Hz trials (M= 1.2 Hz) [F (1, 16) = 50.67, $p < .05$].

A significant Group x Frequency interaction revealed that at 1.0 Hz, there was no significant difference between the two groups (controls M= .99 Hz, PD M= .91 Hz). At 1.5 Hz, the individuals with PD were significantly slower than the target frequency (M=1.1 Hz) than the older adults (M=1.3 Hz) [F (1, 16) = 4.67, $p < .05$].

Two-way interactions between Condition and Frequency [F (1, 16) = 6.82, p < .05] and between Phase and Frequency [F (1, 16) = 9.71, p < .05] confirmed that 1.5 Hz was faster than 1.0 Hz. There was a negligible difference between the compatibility conditions (compatible condition M= .99 Hz, incompatible condition M= .93 Hz) and between the phase patterns (muscular in-phase M= .98 Hz, muscular anti-phase M= .94 Hz) at the slower movement frequency. However, at the faster movement frequency, muscular in-phase (M=1.3 Hz) was significantly faster than muscular anti-phase (M= 1.2 Hz) and the compatible condition was significantly faster (M=1.3 Hz) than the incompatible condition (M= 1.2 Hz).

Involuntary transitions: The operational definition of an involuntary phase transition was the point at which relative phase first deviated more than ±30 degrees from the intended pattern, for a minimum of 2 s. The total number of trials per condition, coordination pattern, and movement frequency were summed across each participant group, yielding a total of 36 trials. Table 2 illustrates the percentage of the 36 trials per group, compatibility condition, phase pattern and frequency, in which an involuntary transition away from the intended pattern occurred. The greatest number of involuntary transitions was made during muscular anti-phase coordination at the faster movement frequency with in-phase visual feedback feedback. Within this particular condition, individuals with PD made an involuntary transition away from muscular anti-phase coordination on 33 % (12/36 trials) whereas the healthy older adults made an involuntary transition away from muscular anti-phase on 27 % (10/36 trials). Involuntary transitions from muscular in-phase to muscular anti-phase were rare for both compatibility conditions. When an involuntary transition away from muscular anti-phase occurred for either compatibility condition, a clear transition to muscular in-phase was never observed. Instead, phase wandering and attempts to reacquire the correct phase relationship were evident, and possibly were due to the task instructions to try and maintain the instructed coordination pattern. These findings reflect the increased coordination demands when the visual information provided by the movement of the flags is incompatible with the movement of the upper limbs, particularly when individuals are responding to in-phase visual information and moving in muscular anti-phase.

Discussion

The purpose of this experiment was to determine whether the basis of preferred phase relationship stability in bimanual coordination in individuals with PD is due to the widely accepted motoric view (Carson et al., 1996; Johnson et al., 1998; Kelso, 1984; Park et al., 2001; Swinnen et al., 2000; Swinnen, Jardin et al., 1997; Swinnen & Van Langendonk et al., 1997) or to the recently proposed perceptual view (Mechsner et al., 2001). In light of the fact that individuals with PD are dependent on visual information to facilitate movement production (i.e., Cunnington et al., 1995; Morris, 2000) and to compensate for a decline in proprioception (i.e., Schneider, 1991; Swinnen et al., 2000), it was predicted that the perceptual view of bimanual coordination would be supported. If the motoric view is the basis of bimanual coordination, then it was expected that regardless of the visual information provided by the movement of the flags, muscular in-phase would be more stable than muscular anti-phase. On the other hand, if the perceptual view is the basis of bimanual coordination, then it was expected that regardless of the movement of the upper limbs, movements that were performed with visual in-phase information would be more stable than with visual anti-phase information.

Analyses of relative phase accuracy and stability provided support for the *motoric* view of bimanual coordination for *both* the individuals with PD and the healthy age- and sex- matched controls. Regardless of the compatibility condition, muscular in-phase was more accurate and more stable than muscular anti-phase coordination. During the compatible condition, muscular in-phase was performed with equivalent accuracy for both movement frequencies, whereas muscular anti-phase was performed with greater absolute mean error at the higher than at the lower movement frequency. During the incompatible condition (in which the flags provided visual information that was opposite to the movement of the upper limbs), movements performed with visual anti-phase feedback were performed with equivalent accuracy for both movement frequencies, whereas movements performed with visual in-phase feedback were performed with greater absolute mean error at the higher than at the lower frequency. That is, similar to the compatible condition, muscular in-phase was performed with equivalent accuracy for both movement frequencies, whereas muscular anti-phase was performed with greater absolute mean error at the higher than at the lower movement frequency. The results from the amplitude and frequency data also provide support for the motoric view. For example, movement frequency and amplitude were closest to their respective targets for muscular in-phase coordination at the slower movement frequency during the compatible condition.

Further support for the motoric view of bimanual coordination is provided by observation of the percent of trials in which an involuntary transition away from the intended pattern occurred (Table 2). Overall, the individuals with PD made the greatest number of involuntary transitions. Both participant groups made involuntary transitions away from muscular anti-phase coordination for both compatibility conditions. In particular the largest percent of involuntary transitions occurred when performing muscular anti-phase coordination with in-phase visual feedback at the higher movement frequency. In contrast, involuntary transitions away from muscular in-phase coordination were rare for either compatibility condition. Therefore, in support of previous research in favour of the motoric view (Kelso, 1984), regardless of the visual information provided by the movement of the flags, muscular in-phase was more stable than muscular anti-phase coordination and there was a tendency for involuntary transitions away from muscular anti-phase to occur.

Overall, these findings suggest that the stability of bimanual coordination for individuals with PD and for healthy older adults is determined by muscular activation rather than by the perceptual qualities of the movement. Similar results were obtained for the healthy older adults and for the individuals with PD. Although individuals with PD are dependent on visual information to facilitate movement performance they did not depend on the visual information provided by the movement of the flags during the incompatible condition. These findings suggest that although PD is associated with a decrease in coordination accuracy and stability, the basis of bimanual coordination is not changed.

Although the results do not support the perceptual view there was some evidence that visual perceptual information influences motor performance. Based on the findings from Mechsner et al. (2001), it was predicted that stability and accuracy of muscular anti-phase would *increase* with visual feedback that was visually in-phase. On the other hand, based on findings from Salter et al. (2002), it was predicted that the stability and accuracy of muscular anti-phase would *decrease* with visual feedback that was visually in-phase and that muscular in-phase would remain stable with incompatible visual feedback. However, trends in the data suggest that *both* muscular anti-phase and muscular in-phase destabilized with incompatible visual information for both individuals with PD and the healthy controls (e.g., Figure 4 & 6). That is, visual perceptual information may have influenced the stability of motor activity.

Compatibility between movement production and visual information provided by the environment may be a determining factor in the stability of bimanual coordination (Chua & Weeks, 1997). The present findings suggest that the intrinsic coordination patterns of older adults and individuals with PD are more susceptible to destabilization when there is incompatibly between upper limb coordination and visual feedback than are the young adults tested by Salter et al. (2002).

Individuals with PD are dependent on visual information to facilitate motor performance (Byblow et al., 2002; Cunnington et al., 1995; Kritikos et al., 1995; Morris, 2000; Praamstra et al., 1998) and to compensate for a PD related decline in proprioception (Demirci et al., 1996; Schneider, 1991; Schneider et al., 1987; Swinnen et al., 2000). However, the results suggest that older adults and individuals with PD experience difficulty integrating *incompatible* visual information to facilitate movement performance. Although coordination performance deteriorates with incompatible feedback, these findings suggest that individuals with PD maintain the ability to perform the intrinsic coordination patterns based on proprioceptive information. Therefore, these findings emphasize the importance of compatibility between visual information and motor performance, especially in patient populations reliant on visual information.

Although the perceptual view of bimanual coordination stability was not supported, results confirm the fundamental differences between the coordination performance of individuals with PD and of healthy older adults. As predicted, the individuals with PD were significantly less accurate and less stable than the healthy older adults. While the individuals with PD did not exhibit bradykinesia at the lower movement frequency, they were significantly slower than the healthy older adults at the higher movement frequency. The amplitude of movement was lower for the individuals with PD, indicative of hypometria. As well, the amplitude of movement of the dominant right hand was significantly greater than that of the non-dominant left hand for both participant groups.

The present experiment only finds potential support for the perceptual view of bimanual coordination for individuals with PD. It could be argued that the perceptual view may be supported if participant's focus of attention was further drawn towards the movement of the flags. For example, light diodes could be used instead of flags. In this case, participants would perform the task as before, however, they would also be required to report when the colour of the diode changed. This would increase the conscious control required to perform the task and may possibly by-pass the defective basal ganglia.

In conclusion, the present experiment strongly supports the motoric basis of upper limb coordination stability in individuals with PD and in healthy older adults. Furthermore these findings emphasize the importance of compatibility between upper limb movements and visual feedback to ensure stability of the intrinsic coordination patterns for individuals with PD.

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Table and Figure Captions

Tables:

Figures:

Table 1: Demographic information on individuals with Parkinson's disease

Age	Sex	Hoehn & Yahr	Duration of disease (yrs)	Medication	Dose	Side of onset	Current side affected	UPDRS I	UPDRS II	UPDRS III	UPDRS IV	MMSE	Controls age
73	F	2	4	Sinemet CR 100-25	4 x daily	Left	L=R	4	19	32	5	25	70
				Requip .25 mg	3 x daily								
80	F	2.5	3	Trihexyphendidyl HCl 2 r	1 x daily	Right	R>L	3	21	35	4	23	82
				Sinemet 100/25 mg	3 x daily								
79	F	3	30	Levodopa/sinemet 100/2	1 tablet 3 x dail	Left	L>R	2	14	27	0	28	77
				Bromocriptine 2.5 mg	1 tablet 3 x daily								
				Selegiline HCl 5 mg	1 daily								
				Amantadine 100 mg	1 daily								
85	M	3	5	Sinemet 100/25	5 x daily	Right	L=R	4	15	46	6	26	88
76	M	3	7	Sinemet CR 200/50	3 x daily	Right	L>R	5	29.5	46.5	1	22	70
				Sinemet 100/25	1 x daily								
59	M	2.5	9	Sinemet CR 200/50	3 x daily	Left	L=R	3	20	31	6	29	57
				Sinemet 100/25 mg	1 x daily								
65	F	3	9	Sinemet CR 200/50	4 x daily	Right	R>L	3	19	45	1	22	65
				Amantadine 100 mg	2 x daily								
57	F	2	7	Selegiline 5 mg	2 x daily	Left	L>R	2	9	26	2	30	60
				Mirapex .5 mg	3 x daily								
72	M	2.5	4	Mirapex .5 mg	3 x daily	Left	L=R	6	20	51	11	27	68
				Prolopa 125	5 x daily								
72		2.61	8.67									25.78	70.78

UPDRS=Unified Parkinson's disease Rating Scale

I=Mentation, Behaviour and Mood

II=Activities of Daily Living

III=Motor Examination

IV=Complications of Therapy

Table 2. Percent of the total 36 trials per block in which an involuntary transition away from the intended pattern occurred

	Compatible Condition				Incompatible Condition			
	Muscular in-phase	Muscular in-phase	Muscular anti-phase	Muscular anti-phase	Muscular in-phase	Muscular in-phase	Muscular anti-phase	Muscular anti-phase
	1.0 Hz	1.5 Hz	1.0 Hz	1.5 Hz	1.0 Hz	1.5 Hz	1.0 Hz	1.5 Hz
Healthy older adults	0%	0%	0%	11%	2.7%	5.5%	11%	27%
Individuals with Parkinson's disease	0%	0%	13%	22%	2.7%	5.5%	22%	33%

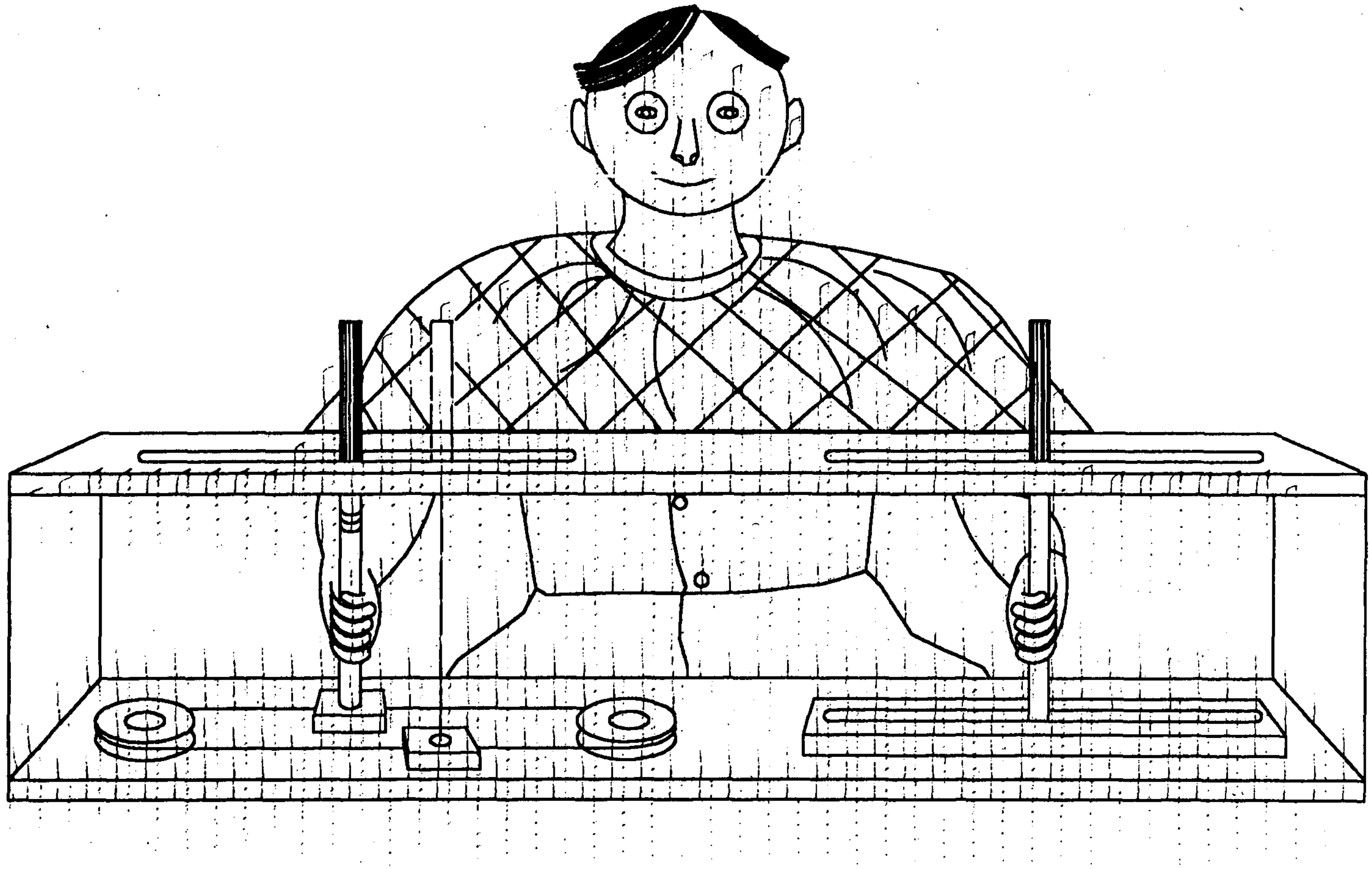
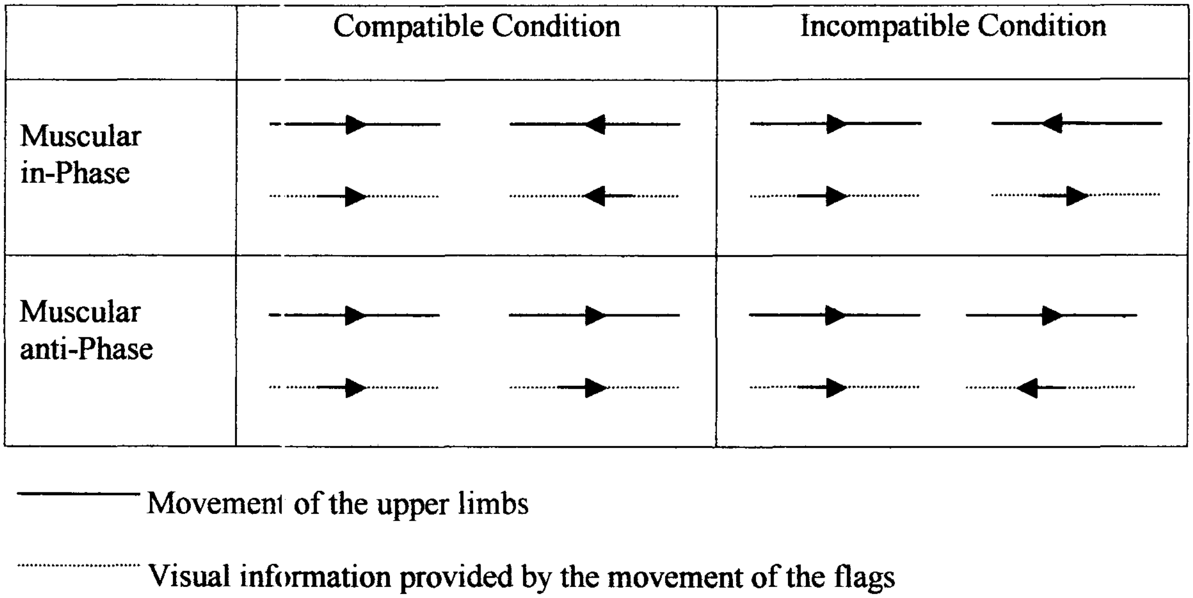


Figure 1. Illustration of apparatus. Participant is wearing a cloth bib to block vision of their upper limbs. Hatched flag indicating set up for the incompatible condition.

Figure 2. Illustration of compatible and incompatible conditions



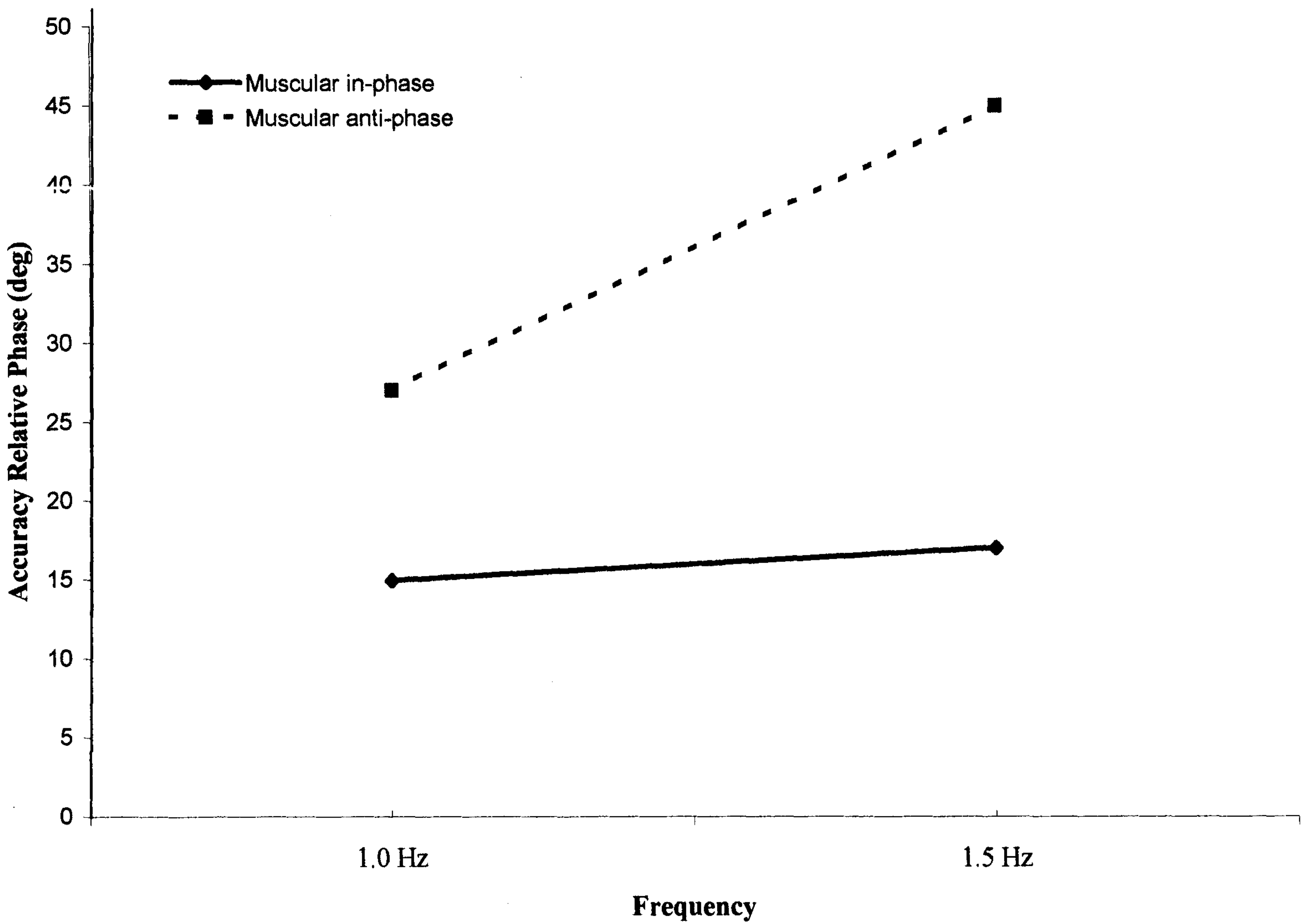


Figure 3: Accuracy: Phase x Frequency [$\underline{F}$ (1 ,16)= 9.59, $\underline{p} < .05$]

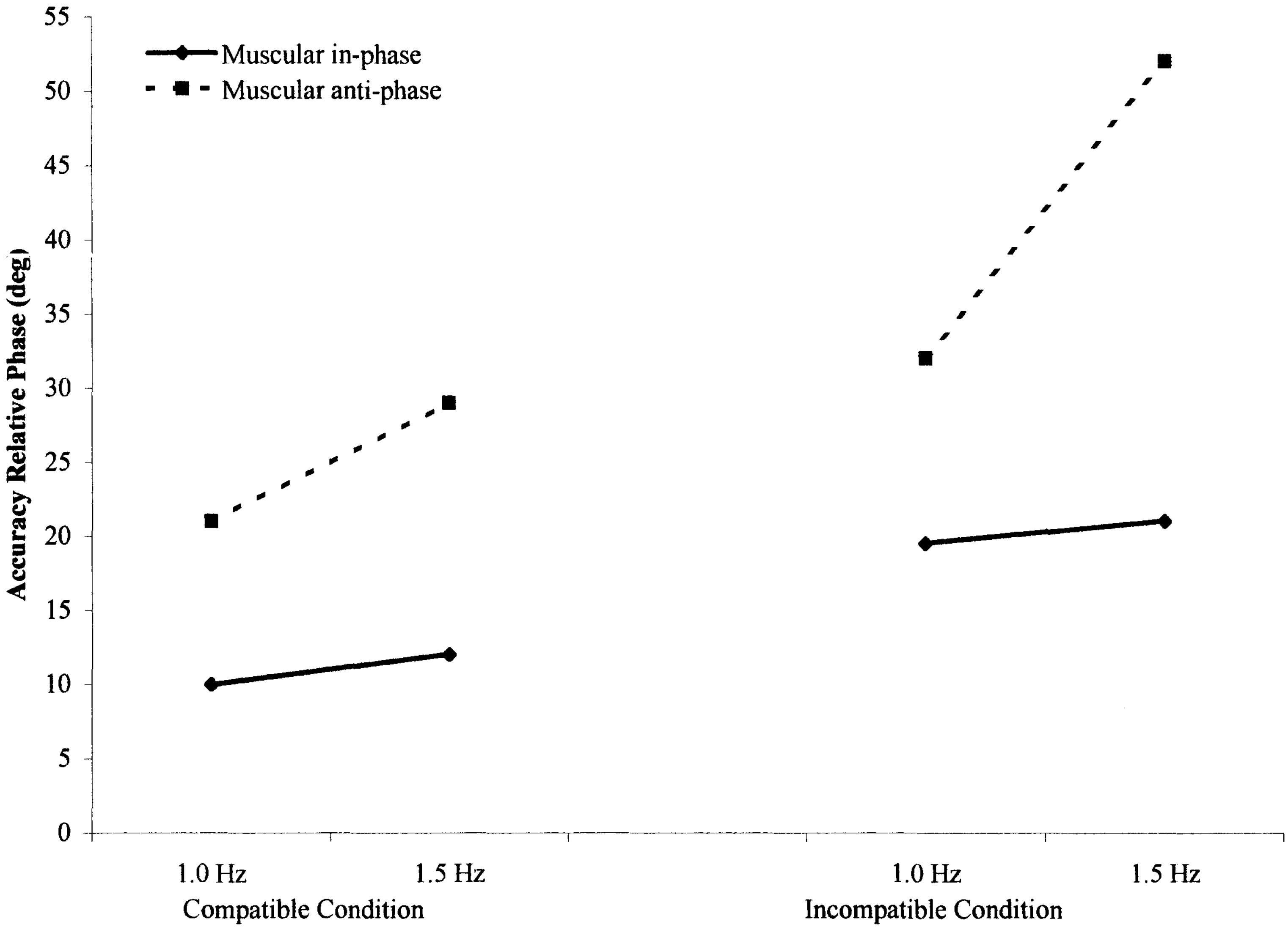


Figure 4: Accuracy: Condition x Phase x Frequency [F (1,16) = 3.68, p = .07]

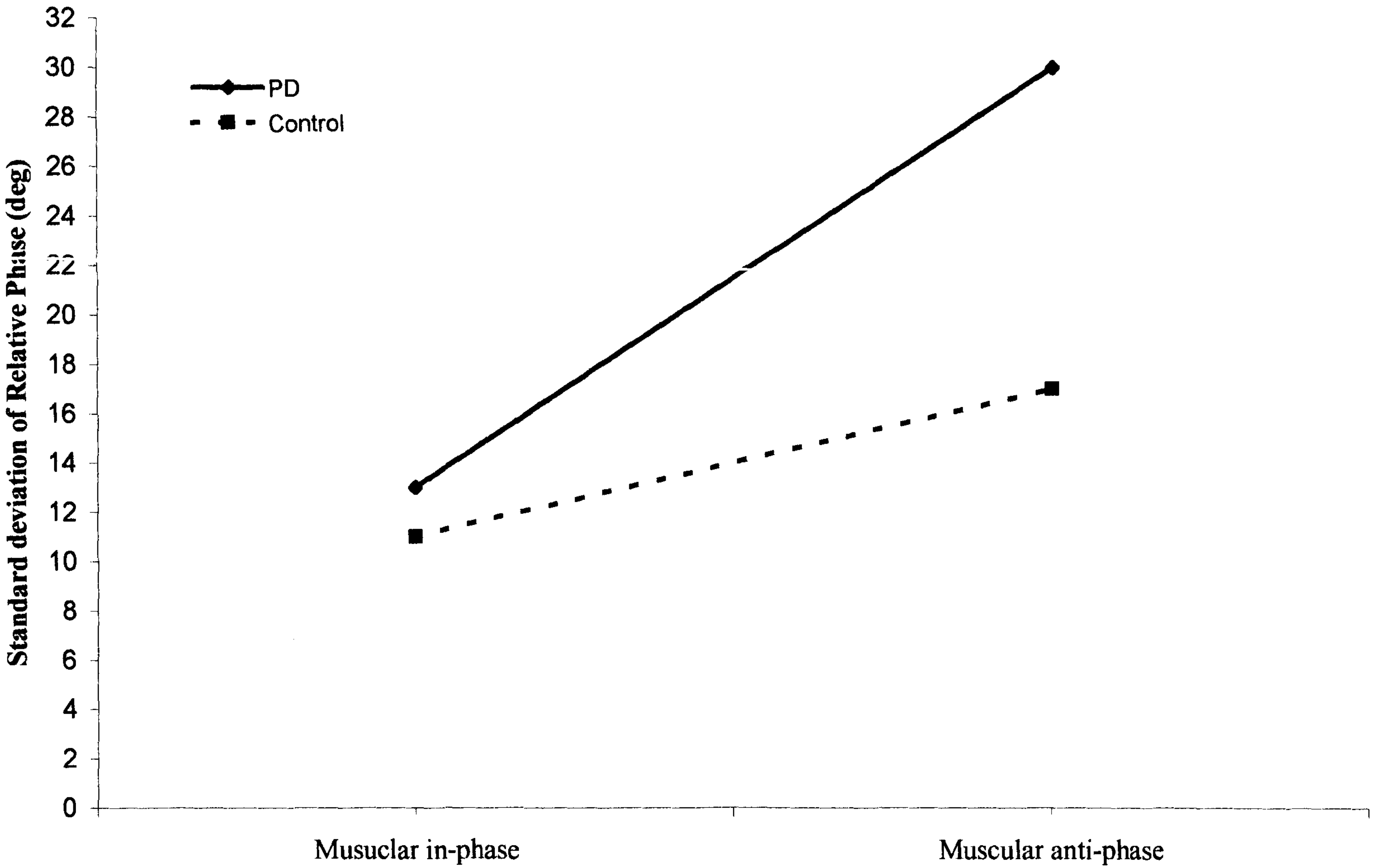


Figure 5: Stability: Group x Phase [$\underline{F}$ (1, 16) = 5.22, $\underline{p} < .05$]

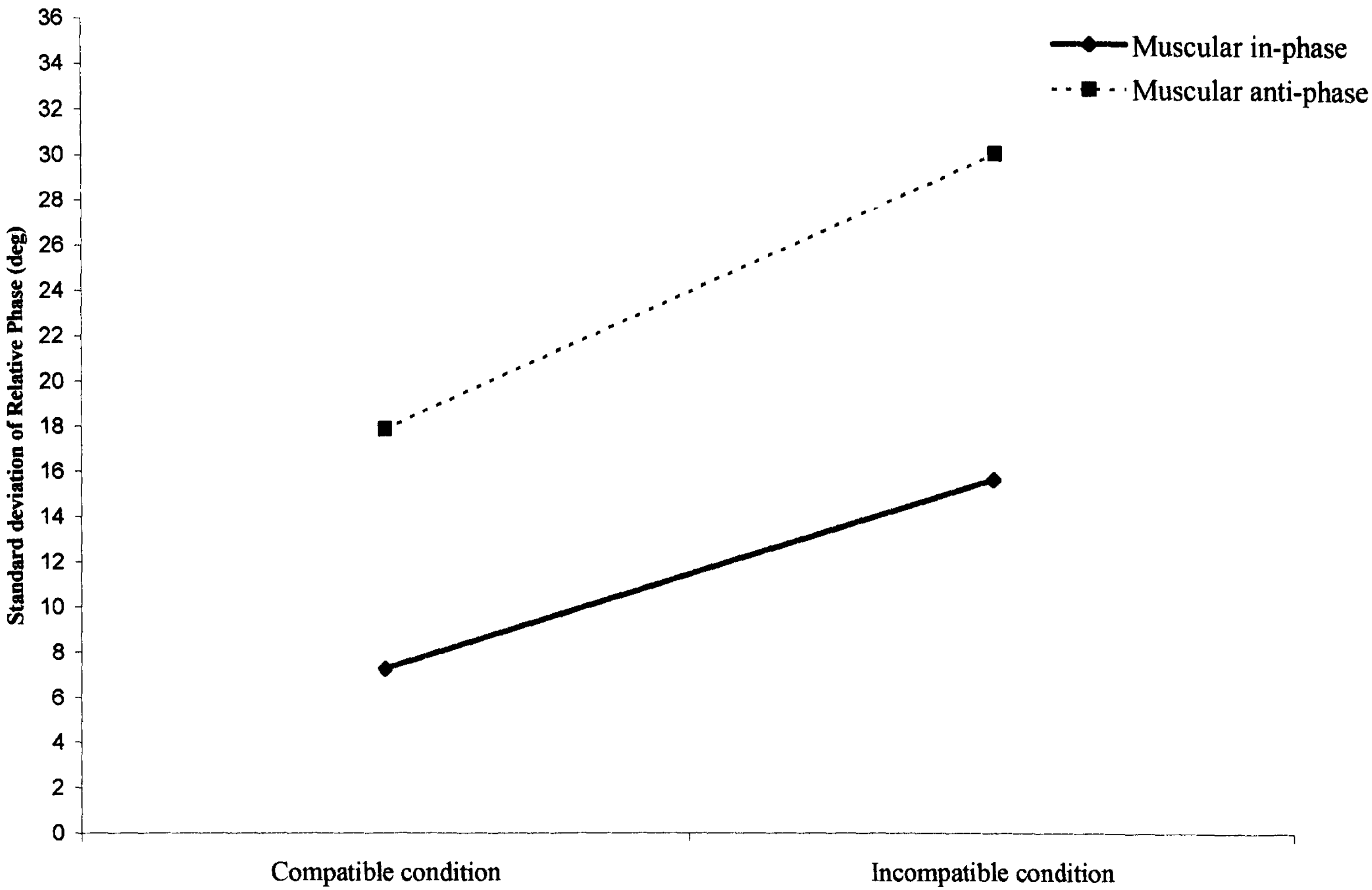


Figure 6: Stability: Condition x Phase [F (1, 16)= 3.59, p=.07]

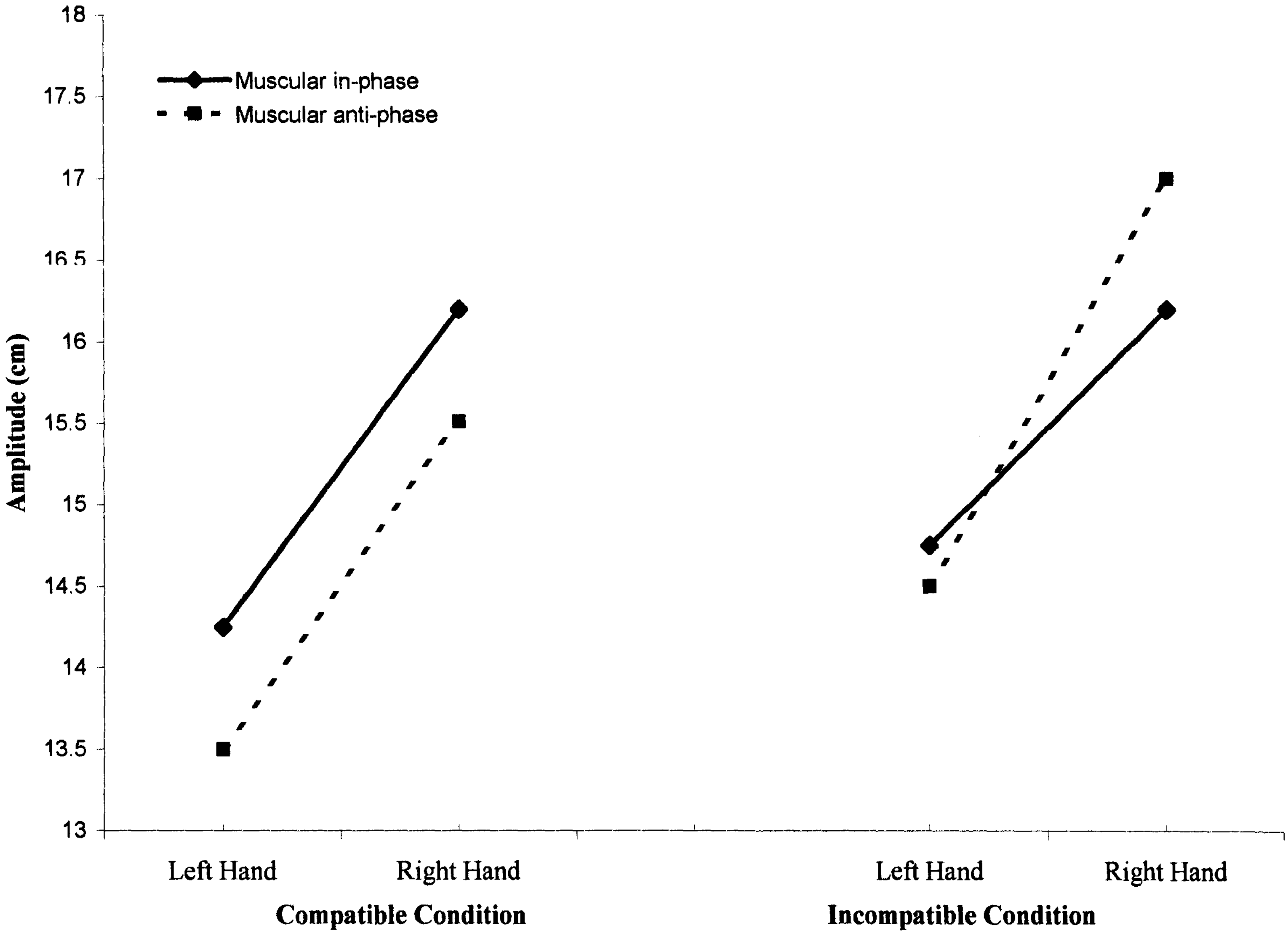


Figure 7: Amplitude: Condition x Phase x Hand [$\underline{F}$ (1, 16) = 6.03, $\underline{p} < .05$]

General Conclusion

The overall purpose of the two experiments described in this thesis was to determine whether the basis of preferred phase relationship stability and accuracy of bimanual coordination is better explained by the widely accepted motoric view or by the recently proposed perceptual view. That is, are in-phase and anti-phase coordination patterns preferred over all other phase relations due to the activation of homologous muscle groups or to how the patterns are visually perceived? More specifically, is in-phase coordination more stable than anti-phase coordination because homologous muscle groups are activated simultaneously or because the movement is visually perceived to be mirror symmetrical? In order to address these questions an experimental task was designed that could compare the motoric versus perceptual views. Healthy, young adults participated in Experiment 1 as a method of determining whether the perceptual view could be replicated with a different experimental task than that used by Mechsner et al. (2001). To determine whether the results of this first experiment could be extended to a different population, individuals with PD and their healthy age- and sex- matched controls participated in Experiment 2. In light of the fact that individuals with PD are reliant on visual information, it was predicted that the perceptual basis would be supported in this patient population.

Overall, the *motoric* view of bimanual coordination was supported with healthy young adults and with the individuals with PD and the healthy older adults. For all participant groups, regardless of the visual information provided by the movement of the flags, muscular in-phase was more stable than muscular anti-phase coordination. These findings suggest that muscular in-phase and muscular anti-phase coordination are preferred over all other phase relationships, possibly due to muscular activity and not to how the patterns are visually perceived. Furthermore, these findings suggest that the mechanisms of stability of bimanual coordination are similar for individuals with PD, healthy older adults, and healthy younger adults.

Although results in general supported the motoric view, there was some evidence that the visual information provided by the movement of the flags influenced the stability of motor coordination. Based on the findings from Mechsner et al. (2001), it was predicted that visual in-phase information would increase the stability and accuracy of muscular anti-phase performance. However, healthy, young adults' performance of muscular anti-phase destabilized when the visual feedback provided by the movement of the flags was in-phase. In contrast, muscular in-phase coordination remained stable and accurate for both compatibility conditions. Healthy older adults and the individuals with PD were more influenced by the visual information provided by the movement of the flags than the healthy young adults. Trends in the results suggest that when visual feedback did not match the movement of the upper limbs, muscular anti-phase *and* muscular in-phase performance destabilized. These findings emphasize the importance of compatibility between visual feedback and the movement of the upper limbs to ensure coordination stability of the intrinsic coordination patterns.

The results from the present experiments lend support to Chua and Weeks (1997) proposal that the concepts of compatibility should be incorporated in dynamic systems theory to assess stability of bimanual coordination. Compatibility between the visual information provided by the environment and the movement of the upper limbs may be instrumental in determining the stability of motor behaviour. As the compatibility between the perception and action is reduced, coordination stability decreases (Buekers et al., 2000; Byblow, Chua, & Weeks, 1997). Indeed, when visual feedback was incompatible to the proprioceptive information from the upper limbs, stability of performance, particularly of muscular anti-phase performance, deteriorated.

A comparison of healthy young and older adults and individuals with Parkinson's disease

In order to determine if the results were consistent across experiments, the data from the 1.5 Hz trials from Experiments 1 and 2 were combined. A comparison of overall performance error between the healthy young adults, individuals with PD and healthy older adults was conducted at 1.5 Hz. Statistical analyses revealed a main effect for Group indicating that the young adults performed with the lowest error of relative phase, followed by the older adults and then the individuals with PD [F (2,36) = 12.41, $p < .05$]. Main effects for compatibility Condition [F (2,36) = 34.88, $p < .05$] and Phase [F (2.36) = 43.17, $p < .05$] were also significant. Muscular anti-phase was performed with significantly greater variability and inaccuracy than muscular in-phase and the incompatible condition was significantly less stable and less accurate than the compatible condition. A Group x Phase interaction [F (2,36) = 3.92, $p < .05$] indicated that muscular in-phase coordination was equally stable and accurate for all three participant groups but that muscular anti-phase performance was significantly less stable for the individuals with PD followed by the healthy older adults. A Condition x Phase interaction [F (2.36)

= 9.58, $p < .05$] showed that the stability and accuracy of both muscular in-phase and muscular anti-phase performance deteriorated with incompatible feedback. This overall analysis provides further support for the motoric basis of bimanual coordination for all three participant groups. Furthermore, the results suggest that muscular anti-phase is significantly more destabilized by visual feedback that is incompatible to the movement of the upper limbs than is muscular in-phase.

Methodological shortcomings

The present experiments may have only found weak support for the perceptual view of bimanual coordination due to methodological shortcomings. One shortcoming of the present experiments was that proprioception from the upper limbs could not be eliminated. Several components of the methodology used in the current experiments were designed specifically to reduce the likelihood that participants would attend to the proprioceptive feedback. For example, participants were instructed and reminded throughout the experiment to concentrate on coordinating the flags in in-phase or anti-phase, no reference was made to the movements of the hands, and a cloth bib prevented participants from watching the movements of their arms and hands. In addition, to change direction of the flags, participants did not physically come into contact with end points but instead relied on the 'in' and 'out' boundary markers. Despite these precautions, the friction from the slide apparatus and the end points of the linear movements may have directed the participants' attention towards the proprioceptive feedback from the upper limbs. However, the specific results related to the visual information conditions suggest that participants were attending to the visual information. As well, participants indicated that they were attempting to achieve the visual goal.

A final methodological factor was that the task may have been too difficult for the individuals with PD to perform. From an initial sample of 11 participants with PD, two were excluded from analysis because they were unable to coordinate the flags in the correct coordination pattern following the practice session.

Future directions

Future studies should address these methodological limitations in an attempt to provide support for the perceptual view of bimanual coordination. Although participants stated that they concentrated on the movement of the flags, in the current experiments, it was impossible to determine the proportion of time in which they actually concentrated on the flags. One method to overcome this problem would be to include a 'Focus of Attention scale' following the completion of each trial. On this scale, participants would indicate the proportion of time throughout the trial that they concentrated on the movement of the flags versus other aspects of movement production (e.g., proprioceptive information from the upper limbs). The methodology of future studies could also include a secondary perceptual task designed to ensure that participants are focusing on the visual perceptual cues, the flags. Here, the flags would be replaced by light diodes. Participants would perform the bimanual coordination task as before; however, they would also be required to report when the colour of the diode changed. This adaptation would augment the degree of attention paid the to the visual cues. Considering individuals with PD are dependent on visual information this adaptation may benefit performance of the intrinsic coordination patterns for this patient population.

In the present experiment, the right flag was transformed by 180-degrees to the dominant, right hand, whereas the left flag and non-dominant, left hand were directly related. This particular transformation was in keeping with the methodology of Mechsner and colleagues (2001). An extension of the present experiments would be to examine bimanual performance with a 180- degree transformation between the non-dominant, left hand and flag with no transformation between the right hand and flag. Right-handed participants attend more to their dominant, right hand than their non-dominant, left hand (Byblow et al., 1999; Peters, 1994). If there was a transformation with the left hand participants may be less likely to concentrate on the incompatibly and instead may focus on coordinating the flags in visual in-phase or visual anti-phase. Consequently, the perceptual view of bimanual coordination may be supported with this methodological variation. A further extension of the present experimental paradigm would be to transform both the right and left flags by 180-degrees relative to the right and left upper limbs, respectively. In doing so, visual in-phase information would be provided during muscular anti-phase coordination and visual anti-phase information would be provided during muscular in-phase coordination. This modification may further dissociate the perceived movement direction of the flags from the movement of the upper limbs. As a result, the perceptual qualities of the movement may dominate muscular activity. An additional variation with individuals with PD would be to only examine participants with unilateral impairment (e.g., stage 2 of the Modified Hoehn and Yahr Staging Scale).

Using this population it would be possible to manipulate the side of flag transformation (i.e., a transformation ipsilateral or contralateral to the impairment) to determine when incompatible feedback destabilizes performance.

The perceptual view of bimanual coordination was only partially supported in the present experiments when bimanual movements were performed in the horizontal plane (parallel to the frontal plane of the body). However, it may be supported when movements are performed in the vertical plane (orthogonal to the frontal plane of the body). The allocentric reference frame of bimanual coordination suggests that movements that are made in the same direction are more stable than movements that are made in different directions (Bogaerts et al., 2002; Swinnen, 2002; Swinnen et al., 1997; Swinnen et al., 1998; Wenderoth & Brock, 2002). In the horizontal plane, visually in-phase movements are mirror symmetrical but the flags move in different directions, whereas visually anti-phase movements are mirror asymmetrical but the flags move in the same direction. However, in the vertical plane, visually in-phase movements are mirror symmetrical *and* the flags move in the same direction, whereas visually anti-phase movements are mirror asymmetrical and the flags move in different directions. Consequently, visually in-phase coordination is most stable in the vertical plane, especially during a compatible condition when homologous muscle groups are activated. (Bogaerts et al., 2002; Swinnen, 2002). A recent experiment by Bogaerts et al. (2002) used a similar paradigm as the present experiments but with linear movements performed in the vertical plane. They found that regardless of the movement of the upper limbs performance was more stable with visual in-phase feedback than with visual anti-phase feedback. These findings suggest that the visual perceptual information provided by the movement may have been important in determining the stability of bimanual coordination. That is, regardless of the movement of the upper limbs, movements that are visually perceived to be mirror symmetrical are preferred over all other phase relations. In sum, the perceptual view of bimanual coordination may be supported if the present experiment was replicated in the vertical plane.

Conclusion

In conclusion, the experiments in this thesis strongly supported the motoric view of bimanual coordination for individuals with Parkinson's disease and healthy, younger and older adults. Potential support for the perceptual view was obtained suggesting further investigation is warranted. These findings emphasize the importance of compatibility between upper limb coordination and visual feedback, particularly during muscular anti-phase coordination.

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Appendix

1. Handedness Questionnaire (Bryden, 1977)
2. Mini-Mental Status Examination (Folstein, Folstein, & McHugh, 1975)
3. Unified Parkinson's disease Rating Scale (Fahn & Elton)

BRYDEN'S MODIFICATION OF CROVITZ HANDEDNESS QUESTIONNAIRE

Name ______________________ Sex: M F Age: ______ Date: ________

Circle appropriate answer:

	Always use left hand	Usually use left hand	Use both equally	Usually use right hand	Always use right hand	Don't know
1) Writing	1	2	3	4	5	6
2) Throwing	1	2	3	4	5	6
3) Drawing	1	2	3	4	5	6
4) Holding a nail to hammer	1	2	3	4	5	6
5) Using scissors	1	2	3	4	5	6
6) Using a toothbrush	1	2	3	4	5	6

Handedness score [ ]

Mini-Mental Status Examination

Name:____________________ Age___ DOB__________ Place Seen__________
Date:
Ask patient:
Name:_______________ DOB_______________ Occupation_______________

Maximum Correct Score	Patient's Score	
		ORIENTATION
5		What is the-date________, day of the week______, month_____ -season__________, year___________
5		Where are we? -name of province_________, town_________ -street_________, place______, floor________
		REGISTRATION
3		Name 3 objects (HOUSE, TREE, CAR). Take 1 second to say each. Then ask the patient all 3 after you have said them. Give 1 point for each correct answer. Then repeat them until he learns all 3. Count trails and record. TRIALS______________
		ATTENTION AND CALCULATION
5		Serial 7's. (100-7)=( )93=( )86=( )79=( )=72=( )65. 1 point for each correct answer. Stop after 5 answers. (Alternatively spell "world" backwards).
		RECALL
3		Ask for the 3 objects repeated above HOUSE( ), TREE( ), CAR( ). Give 1 point for each correct.
		LANGUAGE
9		Name a pencil and watch (,) 2 points Repeat the following "No ifs, ands or buts."________ (1 point) Follow a 3 stage command: "Take a paper in your right hand, fold it in half, and put it on the floor" (3 points) Read and obey the following: "CLOSE YOUR EYES" (1 point) Write a sentence (1 point) Copy design (1 point)
(30)		**TOTAL SCORE**

Unified Parkinson's Disease Rating Scale

I. Mentation, Behavior and Mood

1. **Intellectual Impairment**
   - 0 = None.
   - 1 = Mild. Consistent forgetfulness with partial recollection of events and no other difficulties.
   - 2 = Moderate memory loss, with disorientation and moderate difficulty handling complex problems. Mild but definite impairment of function at home with need of occasional prompting.
   - 3 = Severe memory loss with disorientation for time and often to place. Severe impairment in handling problems.
   - 4 = Severe memory loss with orientation preserved to person only. Unable to make judgements or solve problems. Requires much help with personal care. Cannot be left alone at all.
2. **Thought Disorder** *(Due to dementia or drug intoxication.)*
   - 0 = None.
   - 1 = Vivid dreaming.
   - 2 = "Benign" hallucinations with insight retained.
   - 3 = Occasional to frequent hallucinations or delusions; without insight; could interfere with daily activities.
   - 4 = Persistent hallucinations, delusions, or florrid psychosis. Not able to care for self.
3. **Depression**
   - 0 = Not present.
   - 1 = Periods of sadness or guilt greater than normal, never sustained for days or weeks.
   - 2 = Sustained depression (1 week or more).
   - 3 = Sustained depression with vegetative symptoms (insomnia, anorexia, weight loss, loss of interest).
   - 4 = Sustained depression with vegetative symptoms and suicidal thoughts or intent.
4. **Motivation/Initiative**
   - 0 = Normal.
   - 1 = Less assertive than usual; more passive.
   - 2 = Loss of initiative or disinterest in elective (non-routine) activities.
   - 3 = Loss of initiative or disinterest in day to day (routine) activities.
   - 4 = Withdrawn, complete loss of motivation.

II. Activities of Daily Living *(For both "on" and "off.")*

5. **Speech**
   - 0 = Normal.
   - 1 = Mildly affected. No difficulty being understood.
   - 2 = Moderately affected. Sometimes asked to repeat statements.
   - 3 = Severely affected. Frequently asked to repeat statements.
   - 4 = Unintelligible most of the time.
6. **Salivation**
   - 0 = Normal.
   - 1 = Slight but definite excess of saliva in mouth; may have nighttime drooling.
   - 2 = Moderately excessive saliva; may have minimal drooling.
   - 3 = Marked excess of saliva with some drooling.
   - 4 = Marked drooling, requires constant tissue or handkerchief.
7. **Swallowing**
   - 0 = Normal.
   - 1 = Rare choking.
   - 2 = Occasional choking.
   - 3 = Requires soft food.
   - 4 = Requires NG tube or gastrostomy feeding.
8. **Handwriting**
   - 0 = Normal.
   - 1 = Slightly slow or small.
   - 2 = Moderately slow or small; all words are legible.
   - 3 = Severely affected; not all words are legible.
   - 4 = The majority of words are not legible.
9. **Cutting food and handling utensils**
   - 0 = Normal.
   - 1 = Somewhat slow and clumsy, but no help needed.
   - 2 = Can cut most foods, although clumsy and slow; some help needed.
   - 3 = Food must be cut by someone, but can still feed slowly.
   - 4 = Needs to be fed.
10. **Dressing**
    - 0 = Normal.
    - 1 = Somewhat slow, but no help needed.
    - 2 = Occasional assistance with buttoning, getting arms in sleeves.
    - 3 = Considerable help required, but can do some things alone.
    - 4 = Helpless.
11. **Hygiene**
    - 0 = Normal.
    - 1 = Somewhat slow, but no help needed.
    - 2 = Needs help to shower or bathe; or very slow in hygienic care.
    - 3 = Requires assistance for washing, brushing teeth, combing hair, going to bathroom.
    - 4 = Foley catheter or other mechanical aids.
12. **Turning in bed and adjusting bed clothes**
    - 0 = Normal.
    - 1 = Somewhat slow and clumsy, but no help needed.
    - 2 = Can turn alone or adjust sheets, but with great difficulty.
    - 3 = Can initiate, but not turn or adjust sheets alone.
    - 4 = Helpless.
13. **Falling** *(Unrelated to freezing.)*
    - 0 = None.
    - 1 = Rare falling.
    - 2 = Occasionally falls, less than once per day.
    - 3 = Falls an average of once daily.
    - 4 = Falls more than once daily.
14. **Freezing when walking**
    - 0 = None.
    - 1 = Rare freezing when walking; may have start-hesitation.
    - 2 = Occasional freezing when walking.
    - 3 = Frequent freezing. Occasionally falls from freezing.
    - 4 = Frequent falls from freezing.
15. **Walking**
    - 0 = Normal.
    - 1 = Mild difficulty. May not swing arms or may tend to drag leg.
    - 2 = Moderate difficulty, but requires little or no assistance.
    - 3 = Severe disturbance of walking, requiring assistance.
    - 4 = Cannot walk at all, even with assistance.
16. **Tremor** *(Symptomatic complaint of tremor in any part of body.)*
    - 0 = Absent.
    - 1 = Slight and infrequently present.
    - 2 = Moderate; bothersome to patient.
    - 3 = Severe; interferes with many activities.
    - 4 = Marked; interferes with most activities.
17. **Sensory complaints related to parkinsonism**
    - 0 = None.
    - 1 = Occasionally has numbness, tingling, or mild aching.
    - 2 = Frequently has numbness, tingling, or aching; not distressing.
    - 3 = Frequent painful sensations.
    - 4 = Excruciating pain.

III. Motor Examination

18. **Speech**
    - 0 = Normal.
    - 1 = Slight loss of expression, diction and/or volume.
    - 2 = Monotone, slurred but understandable; moderately impaired.
    - 3 = Marked impairment, difficult to understand.
    - 4 = Unintelligible.
19. **Facial Expression**
    - 0 = Normal.
    - 1 = Minimal hypomimia, could be normal "Poker Face"
    - 2 = Slight but definitely abnormal diminution of facial expression
    - 3 = Moderate hypomimia; lips parted some of the time.
    - 4 = Masked or fixed facies with severe or complete loss of facial expression; lips parted 1/4 inch or more.
20. **Tremor at rest**
    - 0 = Absent.
    - 1 = Slight and infrequently present.
    - 2 = Mild in amplitude and persistent. Or moderate in amplitude, but only intermittently present.
    - 3 = Moderate in amplitude and present most of the time.
    - 4 = Marked in amplitude and present most of the time.
21. **Action or Postural Tremor of hands**
    - 0 = Absent.
    - 1 = Slight; present with action.
    - 2 = Moderate in amplitude, present with action.
    - 3 = Moderate in amplitude with posture holding as well as action.
    - 4 = Marked in amplitude; interferes with feeding.
22. **Rigidity** *(Judged on passive movement of major joints with patient relaxed in sitting position; ignore cogwheeling.)*
    - 0 = Absent.
    - 1 = Slight or detectable only when activated by mirror or other movements.
    - 2 = Mild to moderate.
    - 3 = Marked, but full range of motion easily achieved.
    - 4 = Severe, range of motion achieved with difficulty.
23. **Finger Taps** *(Patient taps thumb with index finger in rapid succession with widest amplitude possible, each hand separately.)*
    - 0 = Normal.
    - 1 = Mild slowing and/or reduction in amplitude.
    - 2 = Moderately impaired. Definite and early fatiguing. May have occasional arrests in movement.
    - 3 = Severely impaired. Frequent hesitation in initiating movements or arrests in ongoing movement.

4 = Can barely perform the task.

24. **Hand Movements** *[Patient opens and closes hands in rapid succession with widest amplitude possible, each hand separately.]*
   0 = Normal.
   1 = Mild slowing and/or reduction in amplitude.
   2 = Moderately impaired. Definite and early fatiguing. May have occasional arrests in movement.
   3 = Severely impaired. Frequent hesitation in initiating movements or arrests in ongoing movement.
   4 = Can barely perform the task.

25. **Rapid Alternating Movements of Hands** *[Pronation-supination movements of hands, vertically or horizontally, with as large an amplitude as possible, each hand separately.]*
   0 = Normal.
   1 = Mild slowing and/or reduction in amplitude.
   2 = Moderately impaired. Definite and early fatiguing. May have occasional arrests in movement.
   3 = Severely impaired. Frequent hesitation in initiating movements or arrests in ongoing movement.
   4 = Can barely perform the task.

26. **Leg Agility** *[Patient taps heel on ground in rapid succession, picking up entire leg. Amplitude should be about 3 inches.]*
   0 = Normal.
   1 = Mild slowing and/or reduction in amplitude.
   2 = Moderately impaired. Definite and early fatiguing. May have occasional arrests in movement.
   3 = Severely impaired. Frequent hesitation in initiating movements or arrests inongoing movement.
   4 = Can barely perform the task.

27 **Arising from chair** *[Patient attempts to arise from a straight-back wood or metal chair with arms folded across chest.]*
   0 = Normal.
   1 = Slow; or may need more than one attempt.
   2 = Pushes self up from arms of seat.
   3 = Tends to fall back and may have to try more than one time, but can get up without help.
   4 = Unable to arise without help.

28. **Posture**
   0 = Normal erect.
   1 = Not quite erect, slightly stooped posture; could be normal for older person.
   2 = Moderately stooped posture, definitely abnormal; can be slightly leaning to one side.
   3 = Severely stooped posture with kyphosis; can be moderately leaning to one side.
   4 = Marked flexion with extreme abnormality of posture.

29. **Gait**
   0 = Normal.
   1 = Walks slowly, may shuffle with short steps, but no festination (hastening steps) or propulsion.
   2 = Walks with difficulty, but requires little or no assistance; may have some festination, short steps, or propulsion.
   3 = Severe disturbance of gait, requiring assistance.
   4 = Cannot walk at all, even with assistance.

30. **Postural Stability** *[Response to sudden, strong posterior displacement produced by pull on shoulders while patient erect with eyes open and feet slightly apart. Patient is prepared, and can have had some practice runs.]*
   0 = Normal.
   1 = Retropulsion, but recovers unaided.
   2 = Absence of postural response; would fall if not caught by examiner.
   3 = Very unstable, tends to lose balance spontaneously.
   4 = Unable to stand without assistance.

31. **Body Bradykinesia and Hypokinesia** *[Combining slowness, hesitancy, decreased armswing, small amplitude, and poverty of movement in general.]*
   0 = None.
   1 = Minimal slowness, giving movement a deliberate character; could be normal for some persons. Possibly reduced amplitude.
   2 = Mild degree of slowness and poverty of movement which is definitely abnormal. Alternatively, some reduced amplitude.
   3 = Moderate slowness, poverty or small amplitude of movement.
   4 = Marked slowness, poverty or small amplitude of movement.

IV. Complications of Therapy *[In the past week.]*

A. DYSKINESIAS

32. **Duration: What proportion of the waking day are dyskinesias present?** *[Historical information.]*
   0 = None
   1 = 1–25% of day.
   2 = 26–50% of day.
   3 = 51–75% of day.
   4 = 76–100% of day.

33. **Disability: How disabling are the dyskinesias?** *[Historical information; may be modified by office examination.]*
   0 = Not disabling.
   1 = Mildly disabling.
   2 = Moderately disabling.
   3 = Severely disabling.
   4 = Completely disabled.

34. **Painful Dyskinesias: How painful are the dyskinesias?**
   0 = No painful dyskinesias.
   1 = Slight.
   2 = Moderate.
   3 = Severe.
   4 = Marked.

35. **Presence of Early Morning Dystonia** *[Historical information.]*
   0 = No
   1 = Yes

B. CLINICAL FLUCTUATIONS

36. **Are any "off" periods predictable as to timing after a dose of medication?**
   0 = No
   1 = Yes

37. **Are any "off" periods unpredictable as to timing after a dose of medication?**
   0 = No
   1 = Yes

38. **Do any of the "off" periods come on suddenly, e.g., over a few seconds?**
   0 = No
   1 = Yes

39. **What proportion of the waking day is the patient "off" on average?**
   0 = None
   1 = 1–25% of day.
   2 = 26–50% of day.
   3 = 51–75% of day.
   4 = 76–100% of day.

C. OTHER COMPLICATIONS

40. **Does the patient have anorexia, nausea, or vomiting?**
   0 = No
   1 = Yes

41. **Does the patient have any sleep disturbances, e.g., insomnia or hypersomnolence?**
   0 = No
   1 = Yes

42. **Does the patient have symptomatic orthostasis?** *[Record the patient's blood pressure, height and weight on the scoring form.]*
   0 = No
   1 = Yes

V. Modified Hoehn and Yahr Staging

Stage 0	No signs of disease.
Stage 1	Unilateral disease.
Stage 1.5	Unilateral plus axial involvement.
Stage 2	Bilateral disease, without impairment of balance.
Stage 2.5	Mild bilateral disease, with recovery on pull test.
Stage 3	Mild to moderate bilateral disease; some postural instability; physically independent.
Stage 4	Severe disability; still able to walk or stand unassisted.
Stage 5	Wheelchair bound or bedridden unless aided.

VI. Schwab and England Activities of Daily Living Scale

[It is O.K. to select a number in between the definitions.]

100%	Completely independent. Able to do all chores without slowness, difficulty or impairment. Essentially normal. Unaware of any difficulty.
90%	Completely independent. Able to do all chores with some degree of slowness, difficulty and impairment. Might take twice as long. Beginning to be aware of difficulty.
80%	Completely independent in most chores. Takes twice as long. Conscious of difficulty and slowness.
70%	Not completely independent. More difficulty with some chores. Three to four times as long in some. Must spend a large part of the day with chores.
60%	Some dependency. Can do most chores, but exceedingly slowly and with much effort. Errors; some impossible.
50%	More dependent. Help with half of chores, slower, etc. Difficulty with everything.
40%	Very dependent. Can assist with all chores, but few alone.
30%	With effort, now and then does a few chores alone or begins alone. Much help needed.
20%	Nothing alone. Can be a slight help with some chores. Severe invalid.
10%	Totally dependent, helpless. Complete invalid.
0%	Vegetative functions such as swallowing, bladder and bowel functions are not functioning. Bedridden.