Bimanual Coordination: 
An Unbalanced Field of Research

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Using more than one limb to perform functional, goal-directed actions is arguably one of the most important abilities that human beings possess. In many everyday tasks, the hands, in particular, must be used to accomplish all manner of goals. From buttoning a shirt to opening a jam jar and driving to work, good bimanual coordination is of great utility. In addition to the tasks mentioned above, there are also other tasks involving the functional use of more than one limb, including walking or cycling and typing a report. With a little thought, it becomes apparent that there is at least one important difference between these categories of coordination tasks. On one hand, in some tasks the effectors must perform markedly different motor outputs that are bound together in some functionally defined and usually object-oriented manner (e.g., buttoning a shirt) yet, in others, the effectors produce very similar motor outputs but in a specific temporal order, which may or may not repeat itself periodically (e.g., walking and cycling compared to typing or drumming). In this short article, I will argue that the second category of coordination task and, in particular, cyclical coordination, has been studied extensively and, at least at the level of behavior, is relatively well understood. In contrast the former category of bimanual task is seldom studied and, even at the descriptive level, is rather poorly understood. One of the reasons for this may be the complexity of such tasks and the technical difficulties involved in attempting to study them. By highlighting some key studies, I hope to illustrate that such tasks can be fruitfully studied in the laboratory. Last, since the neural control processes underlying both classes of coordination task are not yet well known, I aim to draw attention to the potential value of the interventional technique of Transcranial Magnetic Stimulation (TMS) as a tool for investigating the functions of brain regions contributing to bimanual coordination.

**Key Words:** goal directed action, motor control, transcranial magnetic stimulation, human movement
Bimanual coordination has interested researchers for many years. In 1980 Marteniuk and MacKenzie pointed out that two main themes have emerged (at the behavioral level) in the study of bimanual coordination in humans. First, when performing simultaneous, symmetrical movements, the control of the two hands appears to be very similar. Second, when performing asymmetrical, simultaneous movements, obvious interference arises between the two hands. This interference often results in the supposedly different movements of each hand becoming similar and synchronized.

For many motor control researchers, the term bimanual coordination activates an image of two fingers oscillating back and forth with respect to the midline in a mirror symmetrical or parallel fashion. It is well known that bimanual finger movements performed in parallel (i.e., an anti-phase coordination mode) at high frequency demonstrate a spontaneous phase transition such that the movements of the two hands become mirror symmetrical (i.e., in-phase). This classic result reported by Kelso (1984) has been the catalyst for a number of excellent studies examining the ability of the human motor system to produce and control bimanual movements with differing phase relationships between the effectors. Furthermore, the phenomenon has revealed itself both when the temporal and spatial relationship between the effectors is varied. For example, in the spatial domain, when subjects are asked to draw different things, say a line with one hand and a circle with the other, considerable interference arises such that the circle becomes more line-like and the line becomes more circle-like (e.g., Franz, Zelaznik, & McCabe, 1991). Interestingly, when the phase relationship between the hands deviates from an in-phase or anti-phase relationship, participants find it extremely difficult, and arduous practice is required for even partially successful task performance.

The fact that mirror symmetrical movements with respect to the midline comprise the most stable bimanual movement pattern has been termed the egocentric principle (Swinnen, 2002). Over the years, the phase transition at increasing frequency phenomenon has proved to be robust across a whole range of effectors (e.g., Carson, Goodman, Kelso, & Elliott, 1995; Jeka, Kelso, & Kiemel, 1993). When non-homologous effectors (i.e., an arm and a leg) have to be coordinated, the most stable pattern is when both effectors move in the same direction. So for example, coordination of a wrist movement and foot movement performed by a seated subject is best when there is isodirectionality of movements (e.g., both effectors move upwards). This robust phenomenon has been termed the allocentric principle (Swinnen, 2002). Many interesting extensions from these basic results have been made ranging from investigations of how practice can impact upon the ability to perform the most difficult coordination modes to the effects of giving distorted visual feedback and manipulating attentional processes on coordination (e.g., Debaere et al., 2003; Tajima & Choshi, 2000; Temprado et al., 2002; Weigelt & Cardoso de Oliveira, 2003; Wenderoth & Bock, 2001). Swinnen (2002) has written an excellent review detailing some of these studies and the interested reader is referred to this. In addition, the identification of the egocentric and
allocentric principles of bimanual coordination have sparked questions relating to whether the in-phase preferred mode of coordination is more or less the result of simultaneous activation of homologous muscles or isodirectionality of movements (e.g., Baldissera, 1982; Mechsner et al., 2001; Riek et al., 1992).

Whilst cyclical bimanual coordination has been extensively studied and is of great interest and value to researchers interested in the planning and control of human movement, another important category of bimanual coordination tasks has been rather neglected by movement scientists over the years. Figure 1 shows the number of studies that have examined different categories of bimanual coordination tasks and highlights the imbalance in the bimanual coordination tasks that have been examined.

The lack of studies that have investigated object-oriented and goal-directed bimanual tasks is particularly striking. The term goal directed refers to bimanual tasks in which there is a functional object-oriented goal that bears some resemblance to the types of goals typical in real life situations. Hence, by this definition, experiments in which subjects are asked to move their hands (or other effectors) with an instructed phasic relationship at certain speeds do not constitute object oriented goal directed tasks, whereas tasks in which subjects are required to manipulate objects such as drawers, or perform reaching and grasping movements towards objects, are considered object-oriented, goal-directed tasks. I do not wish to imply that studies in which subjects move their hands or other effectors with some instructed phasic relationship are not important, but I do want to highlight the lack of research conducted using object-oriented, goal-directed tasks. The distinction that is made in this paper regarding object orientation, in particular, is

Figure 1 — The types of movement task used in Bimanual Coordination Studies (Pubmed search). Note that many studies have investigated cyclical, rhythmical, and continuous tasks and only very few studies have addressed non-cyclical and object-oriented and goal-directed bimanual coordination tasks.
an important one. Previous authors have highlighted the lack of studies examining discrete movements, object oriented or not, as compared to continuous ones (e.g., Wei, Wertman, & Sternad, 2003). Indeed, a small number of studies have examined the coordination of discrete and oscillatory movements (e.g., Sternad et al., 2000; Wei et al., 2003). Such studies have yielded the suggestion that the basic control processes governing discrete and oscillatory movements are different, with the former being considered (within a dynamic framework) as under the control of fixed-point attractors and the latter controlled by limit-cycle behavior (Sternad et al., 2000). Nevertheless, there remains a lack of research in this area and a greater lack of consideration of object-oriented, goal-directed bimanual coordination.

**Object-Oriented, Goal-Directed Bimanual Coordination**

Wiesendanger et al. (1994) performed one of the first studies in which a goal directed bimanual task involving object manipulation was used. They used a complex pull and pick drawer task in which subjects reached out with their left hand for the handle of a drawer, pulled the drawer open against a load force, while they picked with their right hand a small object placed inside the drawer. The authors reported that, although the onsets of the two reaching movements differed in relation to one another, their goal related end points were highly correlated. Hence, the actions exhibited a goal-related temporal invariance. Perrig, Kazennikov, and Wiesendanger (1999) further examined the time structure of a goal-directed bimanual drawer task and its dependence on task constraints. The bimanual task that was used in this experiment was an adapted pull, pick, and reinsert task of the type originally employed in studies with primates and later with humans (e.g., Kermadi et al., 1997; Wiesendanger et al., 1994). Subjects had to pull open a small drawer with one hand and maintain it in the open position against a closing force, while the other hand reached for the drawer to pick up and reinsert a small peg with a precision grip. Subjects performed the task under a number of different experimental conditions. The normal condition was when there were no constraints imposed by the experimenter, and subjects simply performed the task. Subjects also participated in a condition in which vision was taken away by means of a blindfold and in another condition in which the pulling hand was loaded by adjusting the drawer closing force from 1.5 to 8 N. Subjects performed under other conditions as well: one in which the thumb and the index finger of the pulling hand were anesthetized and a mimicked split-brain condition in which subjects only had to perform the picking with the right hand, while the experimenter performed the reach and pull sequence. In all conditions, the timing at which each movement was made was recorded.

The results showed that, in all subjects, the hands were well synchronized at the goal with high intermanual correlation in reaching the goal (event times of drawer opening and grasping the peg). This high correlation persisted when subjects were blind-folded and were not dependent on movement speed or the highly variable timing of the individual hands. Unilateral loading of the pulling hand and anesthesia of the left index finger and thumb (used for grasping the drawer handle) significantly increased the pull-phase. Interestingly, however, a compensatory slowing of the picking hand
accompanied this slowing of the left hand, and thus temporal goal-invariance was preserved. Furthermore, in the mimicked split-brain condition, all subjects changed their strategy by delaying movement onset of the picking arm so that it started its movement at about the time that the experimenter’s hand approached the drawer handle. Subjects were able to time their right arm movements so that they picked up the peg in near synchrony, with the drawer being opened by the experimenter. However, the correlation coefficients between the hand of the experimenter and the hand of the subject were significantly lower as compared to bimanual performance by the subject alone. This finding is very interesting as it indicated that factors other than vision alone contribute to coordination. The authors interpreted their results as showing that a barrage of multi-modal sensory signals generated in the leading arm may be transmitted centrally to re-parameterize the non-disturbed arm. Alternatively, the fact that the compensation was immediate suggests the possibility of predictive feed-forward processes. In this account, copies of motor signals arising from the motor program for the leading arm could be used to predict the next state of the arm and then parameterize the movement attributes of the non-leading arm. Such predictive signals are thought to be available prior to actual movement and may be generated by an internal forward model of the task (Wolpert & Miall, 1996).

Another object-oriented goal directed bimanual task was studied by Weiss, Jeannerod, Paulignan, and Freund (2000). They made a detailed kinematic analysis of a complex bimanual task comprising picking up a bottle, unscrewing the cap, and placing it down on the table, and then picking up a glass and pouring from the bottle into the glass. This is a common everyday action, but represents an extremely complex task to study in the laboratory. Different subjects preferred to manipulate the objects with different hands, and the results of all subjects were analyzed together irrespective of the differences in effector usage. It was found that there was high execution variability (as found by Perrig et al., 1999) but that the temporal structure of the action could be well characterized by the relative duration and peak velocity of action segments, by the maximum grip aperture object size correlation, and by linear regression analysis between the onsets of functionally related action segments. In particular, analysis of the movement segment in which the hands performed different actions simultaneously (i.e., one hand reached for and picked up the glass while the other hand positioned the bottle ready for pouring), a pattern of synchronization similar to that found by Wiesendanger et al. (e.g., 1994) was observed in which the two hands converged on the same point in time to achieve the goal of the action. The results of Weiss et al.’s suggest that the two arms obeyed a common time structure that ensured their synchronization at critical times during the task. Subjects performed the task in a variety of instruction modalities ranging from actual use of the objects to pantomimed use of the objects, with essentially similar results in all conditions. The authors suggest that such actions may be represented at some level at which all the modalities converge.

Other studies have used reach to grasp tasks to investigate object-oriented, goal-directed bimanual coordination. For example, Tresilian and Stelmach (1997) carried out two experiments in order to examine the organizational principles of unimanual and bimanual reach-to-grasp movements. In the first experiment, subjects had to perform a unimanual and a bimanual reach-to-grasp task. In the
unimanual task, they were required to reach for and grasp an object between the finger and thumb of the reaching hand. In the bimanual task, they were required to reach for the object with both hands but had to grasp the object between the index finger pads of both hands. During both tasks, data related to the kinematic patterns of the movements were recorded. For the unimanual trials, the parameters that the researchers examined ranged from the aperture between the thumb and index finger pads as a function of time, and transport length (distance moved by wrist) to the transport tangential speed. For the bimanual trials, they examined such parameters as wrist aperture, and other measures including tangential speeds of both wrists. The results showed that both the unimanual and bimanual reach-to-grasp movements were performed in a similar fashion by all subjects (despite differences in the biomechanics of subjects’ effector systems). That is, the pattern of aperture preshaping and transport was qualitatively almost identical.

In the second experiment, the investigators manipulated the grasp surface area of the objects. They found that movements were adapted to the new task constraints very similarly in both the unimanual task and the bimanual task. The authors claim that their results support the notion that there is an effector independent level of organization that governs the coordination of movements during performance of reaching and grasping tasks.

Other useful contributions have been made in the area of functional bimanual coordination by Guiard and colleagues. These authors developed innovative laboratory tasks such as the two-handed rod paradigm in which participants had to handle and use a variety of common everyday implements during which their grip preferences were recorded (Guiard & Ferrand, 1996). These studies have shed much light on asymmetries in motor control and “bimanual cooperation.” Guiard et al’s work is exemplary in that effort is made to devise experimental tasks that, whilst being controllable in the laboratory, also preserve some essential features of real-life human actions such as those routinely performed during tool use. This approach represents, in my opinion, a promising method for future research directed at functional, object-oriented bimanual coordination.

The studies highlighted above illustrate that it is possible to examine object-oriented, goal-directed bimanual coordination tasks successfully in the laboratory and to make inferences about the control mechanisms that may contribute to these tasks. The next stage in developing an understanding of the neural systems contributing to such control processes is to employ techniques that allow for the measurement and investigation of brain activity. There are a number of reasons why this next step becomes difficult. First, brain imaging methodologies such as fMRI, PET, MEG, and EEG are subject to high signal-to-noise ratios, and excessive overt movement often exacerbates this problem. Second, and particularly in the case of fMRI and PET, the scanning environment prevents subjects from making functional, object-oriented bimanual actions. Indeed, the only types of bimanual action that lend themselves to study in brain scanners are simple finger movements (e.g., Jancke, 2000). Last, such neuroimaging techniques are expensive and are not within the budget of many research laboratories. In addition to these shortfalls, the fact that correlational imaging methodologies alone cannot provide all the information needed to link structure with function (Walsh & Pascual-Leone, 2003)
makes the situation even more difficult. This is where the interventional technique of Transcranial Magnetic Stimulation (TMS) comes into its own.

**TMS As a Tool for Bimanual Coordination Research**

TMS is used for delivering electrical stimulation to the brain non-invasively via setting up a large, rapidly changing magnetic field in the vicinity of the cortical area to be stimulated (Jahanshahi & Rothwell, 2000). The effect of the induced electrical stimulation arising from the rapidly changing magnetic field is to disrupt normal neural processing in the cortical area(s) underlying the scalp position over which TMS is delivered. The size of the area of cortex affected by TMS can be changed by using different coil types. Typically two types of coil are used, circular coils and figure of eight coils, with the latter providing greater focality of stimulation (Ueno, Tashiro, & Harada, 1988). There are two dominant techniques for using TMS in behavioral research: online single pulse TMS and offline repetitive TMS (rTMS). As stated, online single pulse TMS induces near instantaneous interference to the information processing occurring in the cortical regions being stimulated. In contrast, rTMS can be applied either during or prior to task performance, and depending on the parameters of stimulation can cause cortical excitability to be inhibited or facilitated for a period of time over and beyond the period of stimulation. This offline effect of rTMS has led to the claim that the technique can be used to create “virtual patients.” A major advantage of offline rTMS is that is allows subjects to perform experimental tasks in a naturalistic setting.

**Neural Contributions to Object-Oriented, Goal-Directed Bimanual Coordination: The Case of the Supplementary Motor Area (SMA)**

Brinkman (1984) studied the short-term and the long-term effects of unilateral lesions of the SMA in five monkeys. The task the monkeys had to perform involved obtaining a small amount of food that was lodged in a small hole in a perspex plate. To do this task successfully, the monkeys had to push the food from above and cup their other hand underneath the plate to catch the falling food. Hence, the actions of the two hands were different but were coordinated to achieve a useful result. The monkeys were studied before and after unilateral lesions of the SMA. In all the animals, general behavior was unaffected by the lesions, although for the first few weeks postoperatively, the monkeys all exhibited clumsiness of forelimb movements involving both proximal and distal musculature. In two of the monkeys, even after 1 year of postoperative training, they exhibited bimanual deficits in which the two hands tended to behave in a similar fashion as opposed to sharing the task between them. The likely role of the SMA in bimanual coordination has been highlighted in a number of studies, many using animal models (e.g., Kazennikov, 1999; Kermadi et al., 1997, 1998).

Recently, Obhi et al. (2002) used the technique of rTMS to temporarily disrupt the function of the SMA prior to performance of an object-oriented, goal-directed bimanual coordination task adapted from that used by Perrig et al (1999). In their study subjects were required to perform a pull and catch task in which they opened a
drawer with their left hand and caught a falling ball with their right hand. The timing of all the events in the action was recorded. rTMS to the SMA was found to cause an increase in the movement variability for one critical pair of movements in the action sequence. Specifically, the time between the left hand opening the drawer and the right hand starting its movement to catch the falling ball was significantly more variable after rTMS to SMA. In contrast, there was no effect of rTMS as measured in a control condition in which rTMS was delivered over leg motor cortex or sham stimulation was performed (in which the characteristic clicking sound of TMS is heard, but no electrical activity is induced in the cortex). Taken in conjunction with previous studies in monkeys, these results suggest that the SMA is critical for the control of bimanual actions in which the hands must perform object-oriented, goal-directed actions with a specified temporal relationship. In the task used by Obhi et al. (2002), in contrast to many other studies, the imposed temporal relationship between the hands was not arbitrary (i.e., in phase or out of phase) but functional. That is, the hands had to act together in time in order to catch the ball successfully. Moreover, and importantly for the purpose of this paper, this study clearly shows that the technique of rTMS can be used to investigate the neural systems contributing to measurable behavioral aspects of functional bimanual tasks. A small number of other studies have also used TMS successfully to investigate the role of medial frontal areas in bimanual coordination, although the actions that were investigated were not performed in object-oriented, goal-directed task settings (e.g., Serrien et al., 2002; Steyvers et al., 2003).

**Conclusion**

The purpose of this short paper was not to provide an exhaustive review of the bimanual coordination literature but rather to highlight the imbalance in the field with respect to the type of tasks that have been studied. It has been shown that, whereas coordination principles have been found at the behavioral level for the case of cyclical bimanual coordination, less progress has been made in the understanding of real life, object-oriented, goal-directed tasks both at the behavioral and neural levels. However, key experiments examining these types of bimanual coordination tasks have been highlighted (Perrig et al., 1999; Tresilian et al., 1997; Weiss et al., 2000; Wiesendanger et al., 1994). These studies demonstrate that it is possible to study complex “real world” tasks using temporal and spatial measurement techniques that are readily accessible and widely available. Furthermore, the interventional technique of TMS has been highlighted as a useful tool for understanding the contributions of various brain regions thought to be important for good bimanual coordination. Whilst research into cyclical bimanual coordination tasks should continue, it is hoped that researchers in the field will also consider studying non-cyclical and object-oriented, goal-directed actions in the laboratory. In doing so, at least two functions will be served. First, the imbalance that currently exists in the bimanual coordination literature be redressed. Second, and more importantly, new coordination rules and principles may be uncovered that will improve our general understanding of how the rich variety of bimanual coordination tasks that humans routinely perform are planned and controlled.
References


Acknowledgment

I am grateful to Professor Digby Elliott for providing useful feedback and comments on an earlier draft of this paper.