EXPLORING NON-TASK-RELATED VARIABILITY AS AN AID TO MOTOR SKILL ACQUISITION, RETENTION, AND TRANSFER.

by

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A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF

THE REQUIREMENTS FOR THE DEGREE OF

MASTER OF SCIENCE

in

The Faculty of Graduate Studies

(Kinesiology)

THE UNIVERSITY OF BRITISH COLUMBIA

(Vancouver)

AUGUST 2011

Abstract

In two experiments, we tested whether non-task related variability, in the form of randomly administered mechanical perturbations during practice, would facilitate the acquisition of a novel two-handed coordination movement. There is considerable evidence in the motor learning literature showing that task-related variability, in the form of practice of variations of a skill or practicing skills in a more variable order, can benefit learning and transfer. Moreover, there is recent evidence that non-task related variability added to the learning process, termed differential learning, is beneficial to learning by simply providing a greater exploration of the dynamic environment. In both experiments, we failed to find evidence to support these predictions about the beneficial effects of non-task related variability. In Experiment 1, when variability was administered after a period of stabilization, and in the presence of performance enhancing feedback (i.e., a Lissajous display), no differences between a control group and a variability (perturbation) group were found in retention. This was despite significant improvements for both groups and evidence that the perturbations worked to increase variability later in practice for the perturbation group. In a second Experiment, we increased the amount of practice, changed the feedback display, and provided variability throughout practice. Despite these changes, externally added, mechanical perturbations added to the movement still failed to aid acquisition, retention or transfer. We conclude that this method of practice, when the variability is externally administered and not dependent on performance, fails to aid acquisition or facilitate long term retention or transfer of new motor skills. Therefore, variability, in and of itself, is not a sufficient variable to bring positive changes in performance and learning, considerations

need to be made in regards to the difficulty of the task, the competence of the performer and the specific types of variability, in order to be beneficial.

Preface

A version of chapter 2 has been submitted for publication. Christopher Edwards and Nicola Hodges. (2011) Acquiring a novel coordination movement with non-task related variability.

I conducted all the testing and performed the data analysis. I co-wrote the manuscript with Nicola Hodges. The experiments were designed primarily by me, Christopher Edwards, and by my supervisor, Dr. Nicola Hodges. The other members of my thesis committee, Dr. Ian Franks and Dr. Romeo Chua, provided valuable input and suggestions, particularly in regards to Experiment 1.

Paul Nagelkerke provided technical assistance for programming and experimental setup, with input from me, Christopher Edwards, and Dr. Nicola Hodges.

All research was conducted in accordance with the ethical guidelines of the University of British Columbia with approval from the UBC Behavioural Research Ethics Board, certificate number H08-01794.

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Acknowledgements

I want to thank my fellow grad students who made my time at UBC enjoyable, the faculty who challenged me to be better, and the staff, whose friendly support was always available and necessary. Most of all, I want to thank my supervisor Dr. Nicola Hodges. Your tireless work ethic and passion for research is outstanding. Despite being busier than all of us, you are always there for all your students. Without your time and effort, this would not have been possible. I am sincerely grateful for all you have done for me.

To my thesis committee members Dr. Ian Franks and Dr. Romeo Chua, I thank you for your contributions and your sharing of knowledge. To Paul Nagelkerke, thank you for the laughs, the technical assistance and the continued support.

To my family:

Mum, Dad, and Patrick.

You all inspire me in your own way.

You are my heroes.

1. LITERATURE REVIEW

Creating a practice that maximizes learning, that is the long-term development of participant(s), has been investigated for some time. There is evidence that bringing task-related variability into the practice environment can be a beneficial aid to long-term retention. This variability is most frequently introduced between trials, creating inter-task variability. For example, conditions that require the practice of different variations of a motor skill, such as throwing a ball different distances, have shown to benefit retention and transfer of the skill to new distances in comparison to practice of one task variation (see Van Rossum, 1990). Recent extensions of variability research provides r`eason to believe that adding variation to practice does not need to be related to the task itself and hence structured; similar benefits can be derived from practice when the variations are of a non-task related nature, such as random conditions added to the practice setting. In this more recent research, variability is typically added during the practice of one specific skill or task and creates within trial variability. The aim of this research is to further understand the conditions of practice that are beneficial to the acquisition and long-term retention and transfer of motor skills through examination of non-task related variability as a learning variable and potential teaching aid. This research provides some insight into the underlying principles upon which variability, in general, benefits learning.

1.1 Task Related Variability

1.1.1 Variability of Practice

Task related variability has been investigated mostly in terms of the information-processing framework. Within that framework, task related variability has been defined as variations across trials to the parameters or variables of one class of action, also referred to as a general motor program or schema (Schmidt, 1975). For example, changing the force required to perform an action, such as hitting or throwing a ball is one type of parameter that can be varied within a skill class across practice attempts (i.e., between trial variability). Change to task-related variability in terms of parameters has been referred to as 'variability of practice' (for reviews see: Shapiro & Schmidt, 1982; Van Rossum, 1990).

One prediction of the variability of practice hypothesis is that changing the initial conditions during practice (i.e., bringing in additional task-related variability) will lead to a better developed schema when encountering a new condition, or what is referred to as a transfer test. The idea is that schemas are not formed specific to each movement, but are inferred or adapted from experience. For example, a person is better able to throw 15 meters, after having practiced throwing to distances of 5 meters and 10 meters. A second prediction of this hypothesis is that practicing under varied as opposed to constant practice conditions can enhance the performance of a specific movement. This is based on the idea that the accuracy of the schema (or skill) is improved when multiple initial conditions have been experienced. Movements are never exactly reproduced because of the many degrees of freedom for the performer and because changes to the environment and conditions of performance always exist, at least slightly. Therefore, every movement is a new construction of a schema (Van Rossum, 1990). As such, providing a variety of initial conditions during practice is a better preparation of the schema. For example, practicing throwing distances of 5 m, 10 m, and 15 m results in better throwing accuracy at 10 m than practicing at just 10 m. Support for this proposal has been provided by Shea and Kohl (1990) for instance, who showed that practicing with variations in a parameter feature (i.e., absolute force) of a force production task, led to more accurate force production in retention and transfer tests, in comparison to practicing only the criterion force, referred to as constant practice. Similar benefits were seen for a target-aiming task, where practicing with multiple movement-time-goal variations of the task led to reduced error in accuracy for acquisition and retention in comparison to practicing with only a single variation (Hall & Magill, 1995).

In order to manipulate a task-related parameter or variable of a particular skill, many experimenters investigating variability of practice have chosen to use timing tasks to look at the effectiveness of practice. McCracken and Stelmach (1977) performed two analyses investigating the effects of variability of practice compared to constant practice using a timing task. They were interested in how the various practice conditions impacted performance at a novel timing variation performed at a later date. The variable practice group practiced moving their arm to hit a target under three timing conditions and they were compared to a constant practice group. The first analysis showed that accuracy for the criterion pattern improved slightly over the retention interval for the variable practice group, but it decreased significantly for the constant practice group. Also, the consistency advantage (measured with VE) that existed during practice for the constant practice group disappeared during the immediate and delayed (2-day) transfer tests. In a second analysis, the two groups were compared on a non-practiced transfer task. The variable group was significantly more accurate than the constant group. These results show that variable practice aids both learning and transfer in comparison to constant practice conditions.

Another study that utilized a timing task was conducted by Lee *et al.* (1985). They were interested in the type of transfer that could be facilitated by variable practice conditions. For their transfer tests, they used two durations; 500 ms and 800 ms. The 500 ms duration was inside the range practiced, while the 800 ms was outside. For the inside duration, no differences were observed. However, variable practice was better than constant practice in terms of accuracy on the outside transfer test. These results were taken as evidence that variable practice conditions, in comparison to constant practice of one skill, can benefit the performance of new, related skills, but only when the new skill (or parameter) is outside of the range of movements practiced.

Similar to Lee *et al.* (1985) who investigated transfer to movement durations inside and outside the practice range, Wrisberg *et al.* (1987) investigated how the similarity between practice trials and transfer tests influenced learning. Three different variable practice groups, who practiced three different variations of a timing task, performed more accurately on a transfer task, in comparison to three constant practice groups, who practiced only one movement duration. There were no differences between a variable practice group and a constant practice group who did practice the transfer task. Although there were some variations in findings depending on the performance variable, in general, the variable practice groups performed with less error than the constant practice groups and never the reverse.

It has been inferred from the results of these studies (and others), that providing the information processing system with varied information regarding both intended targets and outcomes enhances a general motor program for a class of actions. An illustration is if one made a plot, with motor commands on one axis and the outcome results on the other axis. For each data point there would be an associated motor command and an outcome. As more targets are attempted, more (different) motor commands would be necessary and therefore this would have a larger spread on the plot. The bigger the spread of results on the plot, the better predictor a 'line of best fit' becomes. If we take the line of best fit as a simplified version of what is intended and the resulting motor command within a class of action, then our motor commands become more accurate and adaptable with variable practice, even at unpracticed conditions.

In summary, there is evidence that variability in the conditions of practice that are related to the skill benefit the performance of a specific skill as well as new, unpracticed skills, specifically those outside the range of practiced task parameters. These benefits have been explained in terms of schema theory and the importance of gaining experience with a variety of conditions and outcomes, which produce a particular action, in order to extrapolate to new actions, or stabilize practiced actions in the face of small changes to the conditions. In this latter case, variability in the nature of practice aids retention by making it more robust to outside influences. Although not explicitly stated, these outside influences could be variables such as forgetting or changes in the environment and stress, variables we explore in the current thesis.

Perhaps not surprisingly, there is also evidence that variable practice conditions result in more variability of the skills during practice (i.e., inconsistency). As such, the skills themselves are less stable than those practiced without change in the parameters across trials. Although this seems to be short-lived (e.g., McCracken & Stelmach, 1977), there is evidence that this inconsistency experienced by variable practice conditions can be detrimental when individuals are attempting to acquire a new skill or general motor program, rather than just a novel task parameter of an already acquired skill. For example, Lai, Shea and colleagues (e.g., Lai & Shea, 1999; Lai *et al.*, 2000; Whitacre &

Shea, 2000, Whitacre & Shea, 2002) have looked at the learning of sequences of key presses that require the learning of both the relative timing between key presses (what they and others refer to as practice of the general motor program) as well as the absolute timing (i.e., a motor skill parameter). Although variability in practice conditions aids absolute timing, particularly for transfer to an unpracticed absolute time, it does not aid the acquisition of the correct relative timing between key presses. This negative effect of variability in terms of the overall movement/program or relative timing feature has been referred to as the 'stability hypothesis' (Shea *et al.*, 2001). However, it is possible that this negative effect is limited to tasks that are already part of the performer's existing skill set (i.e., typing, aiming movements etc.). For novel tasks, involving new coordination configurations between the limbs for example, it is possible that variability will have a beneficial effect on acquisition, aiding the break from more stable, yet unwanted behaviours, as we discuss in sections below.

It has been argued that stability aids the acquisition of a new program for action and, importantly, that too much variation, in both parameters and the order that these practice variables or parameters are practiced (so termed random practice), can have a negative impact on acquisition of the overall skill (see Shea & Wulf, 2005). Below we discuss this second type of task-related variability in practice, termed contextual interference, by comparing blocked and random practice conditions and the processes believed to underlie their relative effects. We also consider how the timing of when variability is introduced in practice impacts on skill acquisition, retention, and transfer.

1.1.2 Contextual Interference

Variability in practice has also been examined in terms of variations to when different variations of a motor skill have been provided. This has typically been examined in a contextual interference paradigm, where a number of different classes of a skill (such as a free-throw shot, a jump shot and a 3-point shot in basketball) are practiced in either a sequential, blocked order (all free-throws, followed by all jump shots, followed by all 3-point shots), or in a random order (free-throw, jump-shot, jump-shot, 3-point, etc.).

The most common finding as a result of changing the order of practice conditions, therefore, the amount of between trial variability, is that blocked practice conditions are usually performed more accurately than random conditions during the acquisition phase; however, random practice is beneficial in retention and transfer to new skills or task parameters (e.g., Shea & Morgan, 1979; Magill & Hall, 1990). The contextual interference effect has been shown across a number of different tasks, domains and populations (see Lee & Simon, 2004 for a review). Although the majority of tasks showing consistent contextual interference effects have been limited to relatively simple discrete timing tasks (such as learning to press 3 different keyboard sequences in certain time goals), there is evidence of advantages for a random in comparison to a blocked practice schedule for the acquisition of novel spatial-temporal bimanual coordination patterns, when comparisons were made to a group who only practiced one task variation on a single practice day (see Tsutsui, Lee, & Hodges, 1998). When the blocked practice group received 3 task variations in a blocked fashion within a practice day, they did not differ in retention from a group who practiced with a random schedule. Therefore, relatively small amounts of variability in practice appear to benefit learning of these more complex coordination skills, as explained in more detail below.

This beneficial effect of random practice has been explained in numerous ways, which are not necessarily mutually exclusive (for reviews see Lee & Magill, 1983; Lee & Simon, 2004). The common theme is memory or retention is improved when more cognitive effort is put into practice. For example, one hypothesis is random practice leads to a more 'distinct' or 'elaborated' memory trace of the skill, due to the greater number of comparisons to other skills. This is known as the 'Elaboration-Distinctiveness' explanation (Shea & Morgan, 1979). Because of these comparisons the skills are believed to be more isolated in memory, thus aiding the retrieval process. Diminished performance during practice is based on the need to keep the patterns or skills distinct from one another. Other researchers believe that the benefits of random practice during retention are related to processes of forgetting and reconstructing (Lee & Magill, 1983; Lee & Magill, 1985). Because the learner forgets the solution, he or she then needs to reconstruct (resolve) the motor problem when a new skill is required during acquisition. During retention, the learner needs to reconstruct the solution, such that practice that involves reconstruction acts to benefit retention. For example, if a person was asked to perform the multiplication of 13 x 17, and they got the answer 221, if they were immediately asked to solve 13 x 17 again, they would not have to resolve the problem a second time, but instead would simply repeat the solution. While there are benefits for retention from random practice, the same process of reconstruction that benefits retention hinders performance during acquisition, as it is simply more difficult to resolve the problem each time. This process of forgetting and reconstruction would only apply to the practice of many tasks across trials. Some other ideas for the benefits of random practice include the notion that random practice is more robust to retroactive interference/ inhibition than blocked practice, because the interval between successive practice and retention of the same skill is not as great as it with blocked practice (Poto, 1988). If three skills are to-be-learned, blocked practice results in more trials between the first and second skills and the retention trials than does random practice, because all of the third skill trials follow both skills (and greater interference for the first skill because both the second skill and third skill trials occur after all the first). The interference caused by learning a similar skill after practice of these similar skills, results in reduced performance of the earlier skills.

It has also been proposed that variability aids motivation of the task (especially for relatively simple laboratory tasks), making it more interesting and challenging for the learner, thus promoting better memory (see Lee & Simon, 2004). This would be the case whether the variability was introduced between trials or within trials. It has also been proposed that in random practice the feedback about performance is less useful because it cannot be readily applied to the next trial. Feedback being less ‘useful’ could be beneficial to performer, as there is considerable research to show that there are costs associated with too much feedback. There are benefits when the learner is required to anticipate and predict their success in the absence of feedback (at least on some trials, see Wulf & Schmidt, 1994). The encouragement to predict or detect errors in performance is assumed to be an important process for motor skill learning in general and all of these explanations for the contextual interference effect implicate error detection and correction processes on some level.

1.1.3 Combining CI and Variability of Practice

As mentioned earlier, researchers have combined the two types of variability (i.e., the amount and how in practice the variability is distributed), in order to determine the most important mechanism underlying these effects. In addition, researchers also look for similarities in the processes underpinning benefits of variable practice conditions. For example, Lee *et al.* (1985) showed that variable practice conditions (i.e., practice of different timing durations) that were administered in a random order (i.e., variable-random) resulted in the best performance during transfer in terms of variability (lower variable error) in comparison to a variable-blocked group and constant practice groups. These findings indicate that practicing with variability, both in terms of task variations and practice order/schedule, leads to stability in performance in later transfer. However, in a second experiment, Lee *et al.* failed to replicate these findings showing the variable-random group to be less accurate (higher mean *ACE*) than the constant group in transfer, even though the variable-block group was more accurate. As noted above, Shea *et al.* (2001) have shown the effects of variability need to be considered in terms of multiple task factors, including whether retention or transfer is examined; as well as, whether relative timing or a new motor program or skill is being acquired, in comparison to acquisition of absolute timing features or parameters. These authors (i.e., Shea *et al.*, 2001) showed negative effects associated with variable-random practice in terms of performance (overall error) at correctly performing the relative durations required in a key-press sequencing task. This was both during practice and in retention/transfer tests. However, benefits from variable-random practice conditions were shown in terms of accuracy of absolute timing related features on transfer to a new, unpracticed overall movement time goal.

The cognitive or information processing demands associated with particular practice conditions are expected to mediate the effectiveness of variable practice conditions (Guadagnoli & Lee, 2004; Shea & Wulf, 2005). This could include things such as how the feedback is presented, the order of practice conditions, the number of tasks to be practiced, the number of parameters to be acquired and the skill-level and age of the learner. Whitacre and Shea (2000) found that variable practice of the force required to perform a force-timing task aided the retention and transfer of the force parameter, but it had negative consequences for the timing parameter, both in terms of stability and error. It might be difficult for a learner to concentrate and attend to improvement of more than one movement goal at a time and, hence, for tasks that have multiple requirements (such as spatial and timing requirements), variability in practice might not be helpful overall.

1.1.4 When to Add Variability into Practice

There is reason to believe that adding interference later in practice has greater benefits to retention and transfer performance of a novel skill than adding (contextual) interference early in practice. This has been attributed to the learner's need to stabilize the movement early, before variability can have any beneficial effects (Shea & Wulf, 2005). Moving from practice with low variability or interference to higher levels has been shown to be beneficial for the acquisition of novel tasks (a barrier knock-down sequencing task, Al-Ameer & Toole, 1993; as well as, a basketball shooting skill, Landin & Herbert, 1997). This is thought to allow the learner time to understand the skill early when the task is challenging, and increase the level of challenge (Guadagnoli & Lee, 2004) and encourage effort at a later point to aid in retention (Albaret & Thon, 1998). Indeed, a number of authors (e.g., Del Rey, 1989; Del Rey, Wughalter, & Whitehurst, 1982; Jarus & Goverover, 1999) have provided evidence to support the claim that interference as a result of a random practice schedule does not provide any learning benefits unless the learners are suitably experienced with the motor skill.

It has also been shown that real-world motor-skill experts choose a schedule that progresses from more blocked to more random when they are able to self-select their practice schedule during practice of novel skills outside of their domain (Hodges & Edwards, in press). This practice strategy benefited accuracy in retention for both the experts and a novice-yoked group that utilized the same schedule, as well as leading to increased satisfaction with practice (which might be related to a motivational benefit of interference later in practice). This was in comparison to a novice group who self-selected a practice schedule with more interference early in practice.

There is indirect evidence that familiarization trials before practice negates some of the positive or negative effects of a random or variable practice schedule. For example, Maslovat, Chua, Lee and Franks (2004) required participants to practice either one or two bimanual coordination patterns (90° and 45° relative phase) following a minimum of 30 trials of familiarization in order to get participants relatively stable at performing a 90° phase offset. Rather than showing an advantage for a blocked schedule in practice and a random group advantage in retention only, the random group was more accurate and more stable than a blocked group during practice as well as retention. Therefore, the potentially beneficial effects of interference in practice can be experienced early, if the movement is relatively familiar before practice and if a sufficient number of practice trials are assessed during acquisition. Interestingly, the authors also showed that a random practice group did not differ from a single-task control group who received twice the number of practice trials of the criterion movement (90° relative phase). This finding indicates benefits for a single task from interference created by practicing a related-task variation.

1.2 Non-Task-Related Variability

1.2.1 Differential Learning

There is recent evidence that the inclusion of non-task related variability in practice leads to improvements in learning. Using a training program termed "differential training" (Schoellhorn, 2000) learning benefits were shown in skilled, adult soccer players for both passing and shooting skills in comparison to traditional practice groups (Schollhorn *et al.*, 2006). The differential training group was introduced to non-task related components during practice, such as receiving the ball with a stiff stance leg, putting their arms up in the air, or leaning their torso during ball reception. Repetitions of the same action were avoided and in the shooting study, external parameters were also varied, such as the ball size, in order to expose the players to variability. In comparison, the traditional practice group practiced with only the criterion action and with many repetitions. Consequently, practicing with variations of a task, that are not related to the to-be-learned skill, improved performance more than traditional practice involving repetition of similar actions. Based on the variability of practice hypothesis and research concerning the optimal time to introduce variability in practice, variability in practice is expected to be beneficial at this late stage of learning or skill level (Shea & Wulf, 2005). However, differential learning benefits have also been noted by these authors for novices when practicing shot put (Beckmann & Schöllhorn, 2003) and there are reported benefits for this practice technique in tennis training (Humpert, 2004; Humpert & Schöllhorn, 2006, cited in Frank *et al.*, 2008) and volleyball (Römer *et al.*, 2003, cited in Frank *et al.*, 2008), although in these latter studies the athletes had some experience. A recent, in-depth analysis of this training technique was provided by Wagner and Muller (2008) who trained a sub-elite athlete in handball skills. To enact differential training the authors combined different step sequences during throwing practice, such that movements were not repeated or that they required less time or more force to complete. They found that the differential training program benefited performance in terms of outcome success and change in movement kinematics. Further, performance dropped for this athlete during a training phase that required practicing only traditional variations of the skill, in comparison to during differential learning practice in the other phases. Although limited by the single performer studied and the lack of a control group, these results again suggest superiority of the differential training program in comparison to traditional variable practice conditions. This furthers the idea that mechanisms of differential training, forcing the learner to adapt and react in continuously new situations, has greater benefits for learning than merely practicing with different variations of the same skill.

Having the learner perform in a constantly changing dynamic environment, such as that of differential learning, can create variability that promotes self-organization and the discovery of optimal motor solution(s) for a given task (Wagner & Muller, 2008; Schollhorn *et al.*, 2006; Beckmann & Schöllhorn, 2003). By introducing variability into the system, arguably the system is aided in its detection of weaker signals, such as, new attractors or behaviours (Schollhorn *et al.*, 2006). Consequently, we might expect that non-task related variability acts to facilitate the learning of new coordination patterns (or attractors), due to the enhancement of error detection processes and a greater experience of possible task dynamics. Indeed, Schollhorn and colleagues argue that learning via differential methods proceeds by a variability-induced bifurcation, rather than a traditionally specified 'to-be-achieved' movement pattern. Experience of various internal and external contexts (acting as control parameters) allows the learner to perform with various dynamics that encourage the emergence of an appropriate task solution for a particular situation, rather than a specified solution. Furthermore, there is evidence that non-task related variability can be beneficially utilized in practice of various sports and perceptual motor tasks and arguably across a variety of skill levels.

1.2.2 Error Augmentation

In the research discussed above, we have talked about variability that has been intentionally added to performance and learning that is independent of the skill level and individual variability levels of the participant. However, there have been attempts to determine whether methods that enhance self-produced variability or errors can act as potential performance and learning aids. The rationale behind the potential success of this error augmentation method is that errors are more clearly identified or detected and corrections are performed more frequently.

In one type of error augmentation protocol, Patton and Mussa-Ivaldi (2004) taught an individual to reach along a curved path trajectory with a robotic arm, whilst movement dependent forces were applied to the limb. These forces were symmetrical to the forces generated by the person when originally learning to move with the robotic device.

Although these opposing forces caused high errors during training, when these forces were removed, the subject reached correctly along the curved path, an after-effect of this type of training. This technique was also used to improve arm movements of stroke patients. Again, mechanical perturbations (forces) were applied to reaching movements in a movement dependent way such that the forces magnified the original errors (Patton *et al.*, 2006; Patton *et al.*, 2001). The stroke patients were able to adapt their arm movements to mechanical perturbations and the error augmentation process aided performance more than unperturbed reaching (see also Reisman *et al.*, 2007, who showed similar after-effects following treadmill perturbations). Therefore, creating errors in the system assisted reaching.

There is also evidence that augmenting the experience of errors early in learning (even on one trial) can actually speed up the rate of acquisition or adaptation. Emken and Reinkensmeyer (2005) analyzed walking adaptations to new viscous force-fields and found that when the magnitude of the force was amplified on the first trial, participants were faster at adapting to the less extreme forces felt on subsequent trials. Accordingly, even transient amplification of errors can aid learning as long as the error causes a change to the motor command on the subsequent movement attempt (Reinkensmeyer & Patton, 2009). It is important to note that the forces applied to augment error in these studies were not random, but were calculated in order to produce a specific (and usually proportional) opposing or symmetrical force, thus leading to desired after-effects following the cessation of the force.

To our knowledge, there is only one study showing that adding more random variability or noise to the system during adaptation (by superimposing a viscous force-field during learning of an inertial force field) and allowing participants to 'play' in the new environment, subsequently benefitted performance in the singular force perturbed environment (Huang, Patton, & Mussa-Ivaldi, 2007). The authors argued that this experience gave performers a richer experience of the task (dynamics) and experience of a wide range of movement states that subsequently benefited later performance in the 'simpler' environment. In one further study both long-term learning and transfer have been examined through general error augmentation methods. In this study Domingo and Ferris (2010), used a spring device to augment errors during beam walking, as well as training participants to walk on a narrower beam, than that they would be tested on, in order to increase the number of errors during practice. However, neither of these approaches led to improvements relative to control groups who practiced the desired task. The techniques designed to increase error, although leading to more falls, did not produce more torso variability and as such, it could be the case that the errors experienced were too large for positive benefits to emerge. Indeed, there was a positive relationship between torso variability and accuracy, suggesting that variability at some level (although this was self-induced) did benefit learning.

Similar error augmentation ideas have been used somewhat effectively to aid learning via manipulations to visual feedback, such that errors look to be larger than experienced (e.g, Brewer *et al.*, 2005; Wei *et al.*, 2005). Again, these data support the idea that overcompensation of errors can have a positive effect on motor performance and learning, regardless of whether the error is motivated by visual or haptic means.

1.3 Coordination Dynamics

The study of movement coordination has been driven by the theoretical framework of non-linear dynamics and what has become known as coordination dynamics (Kelso, Southard, & Goodman, 1979). Much of the research has focused on understanding the coordination between two limbs within a person, although between person coordination and single limb coordination have also been studied (e.g., Schmidt, Carello, & Turvey, 1990; Schöner, 1990). Bimanual coordination was modeled and conceptualized by Haken, Kelso and Bunz (1985) in terms of a dynamic landscape characterized by bi-stability. The bi-stable nature of bimanual coordination was due to the observation that in-phase (typically defined by the synchronous or simultaneous flexion and extension of homologous muscle groups, resulting in approximately 0° offset between the relative positions of the limbs at any point in time) and anti-phase (typically defined by the alternating flexion and extension of homologous muscle groups, resulting in approximately 180° offset between the relative positions of the limbs at any point in time) coordination are most frequently and stably observed when people are asked to move their limbs to coordinate with various stimuli.

In bimanual coordination, stability and instability have been demonstrated through manipulations to speed, perturbations to the movement and learning. Most notably, in the face of increasing speed constraints the anti-phase pattern destabilizes (i.e., variability in the phasing of the limbs increases and eventually gives rise to in-phase). Because of the apparent 'pull' of the anti-phase pattern toward the in-phase pattern at high movement speeds, it was argued that in-phase was a strong attractor, whereas at low movement speeds, the bimanual system is bi-stable with two stable attractors (Haken, Kelso, & Bunz, 1985).

These stable attractors cause difficulty for learning new coordination movements. It has been shown that learning requires a 'break-away' from these stable attractors in order to acquire and stabilize a new coordination pattern such as 90° relative phase (see Hodges & Franks, 2000; Hodges & Franks, 2002; Zanone & Kelso, 1997; Zanone & Kelso, 1992). The 90° pattern has received most attention because conceptually it lies half way between the in-phase and anti-phase patterns and, therefore, should be difficult to acquire because of the attraction to both these patterns. In repeated studies it has been shown that new coordination patterns can be learnt and stabilized given the right feedback conditions (e.g., Hodges & Franks, 2001; Lee, Swinnen & Versheuren, 1995). In addition, there is evidence that variability is needed early in practice to break away from these stable movement patterns (Hodges & Franks, 2000; Hodges & Franks, 2002; Hodges & Lee, 1999) and that retention performance is positively related to this variability seen early in learning (e.g., Hodges & Franks, 2000). It is likely, specific types of augmented feedback act to enhance early learning through enhanced variability (i.e., Lissajous feedback, involving a relative phase plot of the left-limb vs. the right limb, such that a circle pattern specifies correct performance of the 90 degree relative phase pattern, see Hodges & Franks, 2002).

The continuous, bimanual coordination task is a useful tool to study the skill acquisition process as we look at a learner's spectrum of abilities across variations of the task (often referred to as scanning). It allows us to investigate the learning of new skills in relation to known attractors, given that there are very few tasks that allow such a clear picture of landscape of abilities before practice. Although it is generally understood that we learn any new skill on top of an existing skill set, the bimanual coordination task allows comparisons to be made across many related skills, before, during and after practice, in terms of rate of acquisition, retention and transfer performance.

In addition to providing a novel and relatively difficult task to learn in controllable and measureable conditions, new bimanual coordination patterns can be learned over short period of practice. It has been argued that the learning of new coordination patterns allows assessment of general principles of movement due to the fact that many real world skills require the coordination between limbs, such as learning to juggle or play the piano.

1.3.1 Information Processing and Coordination Dynamics

There have been attempts to bring together ideas and concepts that are generic to information processing theories and those of coordination dynamics. Shea and Wulf (2005) discuss general motor programs as attractor landscapes, such that a preference for a particular movement is acquired which, depending on the size of the potential well, attracts other nearby movements. In both schema theory and coordination dynamics, the learned movement or preferred intrinsic movement is assumed to be somewhat abstract or stored in a generic fashion. This is evidenced by positive transfer, particularly in terms of effectors. In coordination dynamics, transfer gives an indication of the symmetry or otherwise of a dynamical landscape and it is assumed that when learning takes place it affects the whole landscape and not just the to-be-learned pattern (Schoner & Kelso, 1988; Haken, Kelso, & Bunz, 1985; Zanone & Kelso, 1997). In information processing terms, transfer is assumed to reflect the generality of the motor program and how it is highly influenced by the type of practice conditions experienced, particularly with respect to variability in these conditions. In dynamics' terminology, variability within actions is important for change, but little has been said about variability between various types of actions.

1.3.2 Task Related Variability and Acquiring New Coordination Movements

Another benefit to using the bimanual coordination task is that there is an existing body of research that has shown benefits to learning from task-related variability added across trials (e.g., Maslovat, Chua, Lee, & Franks, 2004; Tsutsui, Lee, & Hodges, 1998). This is in terms of both the acquisition of a number of different coordination patterns, with different relative phase requirements, as well as for the acquisition and stabilization of a single pattern as a result of added interference. Therefore, even for this relatively difficult skill, variability is potentially useful and beneficial for retention and transfer. To date, however, there have been no attempts to study the effects of variability within a trial. As detailed above, there is evidence that variability (both within and across trials), facilitates abandoning stable, yet, unwanted movement patterns (such as in and anti-phase) and, as such, there is reason to think that adding variability early in practice will aid both acquisition and later retention (see also Schollhorn *et al.*, 2006).

1.3.3 Non-Task Related Variability and New Coordination Movements

Based on the above review, there is cause to believe that added variability will assist in breaking away from natural, yet undesired attractors. It has been shown that transitions to new patterns (either as a result of perturbations, a change in constraints such as increased speed, or learning) are preceded by increased variability in the current level of performance (e.g., Haken *et al.*, 1985; Zanone & Kelso, 1992). Therefore, benefits to learning in terms of breaking away from attractors, created from this natural unintentional variability, could be enhanced by adding non-task related variability to the skill.

1.4 Thesis Rationale

We propose to determine whether intentional, non-task related variability (i.e., variability that is not part of the task goal, but is potentially relevant to the task), can serve as an aid to learning a novel coordination movement. We aim to create non-task related variability by adding mechanical perturbations at various times during the movement. For the task of bimanual coordination a mechanical perturbation will create variability in the primary aspect of the task – the movement itself.

Mechanical perturbations added to the limbs during practice trials are expected to work in two possible ways. Based on the literature reviewed above, this non-task related variability is expected to create interference and perhaps enhance cognitive effort (especially later in practice) in order to aid retention. In a similar manner to mechanisms proposed for interference created by practicing variations of a skill in a random order, we expect that variability, once the motor skill has been acquired and somewhat stabilized, will engage error detection and correction processes in order to better stabilize and perform the newly acquired movement. We also expect that these perturbations will add variability to the movements in order to aid performance early in learning in breaking away from more stable attractors, such as in-phase and anti-phase (see Hodges & Franks, 2002). Therefore, variability is expected to aid the rate of acquisition, which might impact on the long-term retention of this skill.

In order to determine when and how variability affects acquisition and learning, we conducted two experiments. Variability was induced via small mechanical perturbations given late in practice in Experiment 1 or throughout practice in Experiment 2. No perturbation control groups were also tested for each experiment.

2. ACQUIRING A NOVEL COORDINATION MOVEMENT WITH NON-TASK RELATED VARIABILITY

2.1 General Introduction

There is evidence that bringing task-related variability into the practice environment can be a beneficial aid to long-term retention (for reviews see Lee & Simon, 2004; Van Rossum, 1990). Recent extensions of variability research provide reason to believe that adding variation to practice does not need to be related to the task itself and benefits can be derived from practice when the variations are of a non-task related or random nature (e.g., Schollhorn *et al.*, 2006). Our aim in the following two experiments is to further test the conditions of practice that are beneficial to the acquisition, retention and transfer of motor skills through examination of non-task related variability as a learning variable and potential teaching aid. We use a controlled laboratory task to test the efficacy of this approach, due primarily to advantages that can be gained from control of the variability and measurement of improvements.

2.1.1 Task-Related Variability

Task related variability has been investigated mostly in terms of the information-processing framework. It has been defined as variations across trials to the parameters of one class of action (e.g., changing the force required to throw a ball different distances). This has been referred to as 'variability of practice'. Added parameter variability has been shown to benefit retention and transfer in comparison to 'constant' practice conditions (for reviews see Shapiro & Schmidt, 1982; Van Rossum, 1990). Variability in practice has also been examined in terms of variations to when different variations of a motor skill have been provided. This has typically been examined in a contextual interference paradigm, where a number of different classes of a skill (such as a free-throw shot, a jump shot and a 3-point shot in basketball) are practiced in either a low variability (blocked) or high variability (random) schedule. The most common finding as a result of bringing in variability to the order that skills are practiced, is that blocked practice is usually performed more accurately than random practice, but that random practice leads to better retention and transfer (e.g., Shea & Morgan, 1979; Magill & Hall, 1990; Lee & Simon, 2004).

The proposed mechanisms underlying the beneficial effects of variability in practice as a result of these two methods are believed to be a result of the cognitive operations experienced during practice, as well as the varied experience of the sensory-motor conditions. In both cases, variability is thought to enable a more developed (stable) representation of a movement (see for example, Shea & Kohl, 1990). The encouragement to predict or detect errors in performance is assumed to be an important process for motor skill learning in general and explanations for the beneficial effects of task-related variability implicate the involvement of error detection and correction processes on some level.

There is evidence that adding interference or variability later in practice has greater benefits to retention and transfer performance of a novel skill than adding it early. This has been attributed to the learner's need to stabilize the movement, before variability can have any beneficial effects (Shea & Wulf, 2005). Moving from practice with low variability or interference to higher levels has been shown to be beneficial for the acquisition of novel tasks (e.g., Al-Ameer & Toole, 1993; Landin & Herbert, 1997). This is thought to allow the learner time to understand the skill early when the task is challenging, and increase the level of challenge (Guadagnoli & Lee, 2004) and encourage effort at a later point to aid in retention (Albaret & Thon, 1998).

Similar conclusions about withholding variability until later in practice have also been reached from reading of the variability of practice literature. For example, Lai, Shea and colleagues (e.g., Lai & Shea, 1999; Lai *et al.*, 2000; Whitacre & Shea, 2000, Whitacre & Shea, 2002) showed that for key-press, sequence learning task, variability in practice aided retention of the overall timing of the sequence, but that it did not aid acquisition of the correct relative timing between key presses. This has been referred to as the 'stability hypothesis' (Shea *et al.*, 2001). However, it is possible that this negative effect is limited to tasks that are already part of the performer's existing skill set (i.e., typing, aiming movements etc.). For novel tasks, involving new coordination configurations between the limbs, it is possible that variability will have a beneficial effect on learning aiding the break from more stable, yet unwanted behaviours, as we discuss below.

2.1.2 Non-Task-Related Variability

Although the majority of the research on motor skill acquisition and variability has been conducted with respect to task-related variability, there is recent evidence that non-task related variability in practice potentially benefits performance and learning. Using a training program termed "differential training" (Schöllhorn, 2000) learning benefits were shown in skilled soccer players for both passing and shooting skills in comparison to traditional practice groups (Schöllhorn *et al.*, 2006). The differential training group was introduced to non-task related components during practice, such as receiving the ball with a stiff stance leg, putting their arms up in the air, in comparison to a traditional practice group who repetitively practiced only the criterion action. Consequently, practicing with variations of a task, which are not related to the to-be-learned skill, improved performance more than single task, repetitive practice. Differential learning benefits have also been noted by these authors for novices when practicing shot put (Beckmann & Schöllhorn, 2003) and there are reported benefits for this practice technique in tennis training (Humpert 2004; Humpert & Schöllhorn, 2006, cited in Frank *et al.*, 2008) and volleyball (Römer *et al.*, 2003, cited in Frank *et al.*, 2008), although in these latter studies the athletes had some experience. These studies support the idea that mechanisms of differential training, forcing the learner to adapt and react in continuously new situations, benefits learning rather than just merely practicing with different variations of the same skill.

Having the learner perform in a constantly changing dynamic environment, such as that of differential learning, can create variability that promotes self-organization and the discovery of optimal motor solution(s) for a given task (Wagner & Muller, 2008; Schollhorn *et al.*, 2006; Beckmann & Schöllhorn, 2003). By introducing variability into the system arguably the 'system' is aided in its detection of weaker signals, such as, new attractors or behaviours (Schöllhorn *et al.*, 2006). Consequently, we might expect that non-task related variability will act to facilitate the learning of new coordination patterns (or attractors), due to the enhancement of error detection processes and a greater experience of possible task dynamics. Indeed, Schöllhorn and colleagues argue that learning via differential methods proceeds by a variability-induced bifurcation, rather than a traditionally specified 'to-be-achieved' movement pattern. Experience of various internal and external contexts allows the learner to perform with various dynamics that encourage the emergence of a context-appropriate task solution rather than a specified solution.

There is also some experimental evidence to support this idea that adding non-task related variability aids experience of the task (dynamics) and a wide range of movement states. For example, participants adapted to a single, inertial force field environment following either reaching practice in this environment, or following exposure to this environment when a viscous force-field was additionally added. Participants who were allowed to ‘play’ in the ‘dual’ environment, showed benefits beyond the single force group when tested in the single force environment (Huang, Patton, & Mussa-Ivaldi, 2007). This technique is based on learning methods that are founded on the principle of error augmentation. Accordingly, variability is intentionally added to performance/practice, but this variability is typically dependent on current performance, such that self-produced errors are enhanced. The rationale behind the potential success of this error augmentation method is that errors are more clearly identified or detected and corrections are performed more frequently.

In one type of error augmentation protocol, Patton and Mussa-Ivaldi (2004) taught an individual to reach along a curved path trajectory with a robotic arm, whilst movement dependent forces were applied to the limb. These forces were symmetrical to the forces generated by the person when originally learning to move with the robotic device. Although these opposing forces caused high errors during training, when these forces were removed, the subject reached correctly, an after-effect of this type of training (see also Patton *et al.*, 2001; Patton *et al.*, 2006). However, in a related study that involved beam walking (Domingo & Ferris, 2010), a spring device worn to augment errors as well as training with a narrower beam than required on the final test, did not aid learning in comparison to appropriate controls. The authors found that these error enhancing techniques, although producing more errors (falls), did not produce more torso variability, and it was this latter variable that was found to be positively related to accuracy in retention. Moreover, an assisted group, where errors were prevented (i.e., falls), did perform worse than non-assisted groups in retention. Therefore, although forced errors did not aid learning in this study, some variability was beneficial and the prevention of errors was actually a hindrance.

There is also evidence that augmenting the experience of errors early in learning (even on one trial) can actually speed up the rate of acquisition or adaptation. Emken and Reinkensmeyer (2005) analyzed walking adaptations to new viscous force-fields and found that when the magnitude of the force was amplified on the first trial, participants were faster at adapting to the less extreme forces felt on subsequent trials. Accordingly, even transient amplification of errors can aid learning as long as the error causes a change to the motor command on the subsequent movement attempt (Reinkensmeyer & Patton, 2009).

2.1.3 Bimanual Coordination and Variability

In bimanual coordination, stability and instability have been demonstrated through manipulations to speed, perturbations to the movement and learning. Most notably, in the face of increasing speed, anti-phase movements (i.e., alternating flexion and extension of same muscle groups across the two arms/hands, also referred to as 180° relative phase, RP) destabilize and the variability in the phasing of the limbs increases and eventually gives rise to in-phase coordination (i.e., same pattern of flexion and extension across the same muscle groups of both arms, 0° RP). Because of the apparent 'pull' of the anti-phase pattern toward the in-phase pattern at high movement speeds, it was argued that in-phase was a strong attractor, whereas at low movement speeds, the bimanual system is bi-stable with two stable attractors (Haken, Kelso, & Bunz, 1985).

These stable attractors cause difficulty for learning new coordination movements. It has been shown that learning requires a 'break-away' from these stable attractors in order to acquire and stabilize a new coordination pattern such as 90° RP (see Hodges & Franks, 2000; Hodges & Franks, 2002; Zanone & Kelso, 1997; Zanone & Kelso, 1992). In repeated studies it has been shown that new coordination patterns can be learnt and stabilized given the right feedback conditions (e.g., Hodges & Franks, 2001; Lee, Swinnen & Versheuren, 1995). It is likely that specific types of augmented feedback act to enhance or reduce variability either early or late in practice, to aid the break from stable attractors (early) or stabilize performance (later). One type of feedback that has been shown to be a useful guiding source of information is Lissajous feedback, which is a relative phase plot of the left-limb plotted against the right limb, such that a circle pattern is produced when an individual correctly performs a 90° RP pattern (see Hodges & Franks, 2002; Kovacs & Shea, 2011).

In addition, there is evidence that retention performance is positively related to this variability seen early in learning (e.g., Hodges & Franks, 2000). Indeed, in one study, Maslovat, Chua, Lee and Franks (2004) found that random practice of 2 RP movements (i.e., 45° and 90° RP), was more beneficial than blocked practice for retention (see also Tsutsui, Lee, & Hodges, 1998), but also for acquisition. This suggests that early variability had a beneficial practice effect. However, in this study participants were given a number of familiarization trials before practice began. To date, there have been no attempts to study the effects of variability within a trial even though there is reason to think that adding variability, both early and late in practice, will aid acquisition and later retention.

In addition to providing novel and relatively difficult tasks to learn in controllable and measureable conditions, new bimanual coordination patterns can be learned over a short period of practice. It has been argued that the learning of new coordination patterns allows assessment of general principles of movement due to the fact that many real world skills require the coordination between limbs, such as learning to juggle or play the piano. In coordination dynamics, transfer gives an indication of the symmetry or otherwise of a dynamical landscape and it is assumed that when learning takes place it affects the whole landscape and not just the to-be-learned pattern (Schoner & Kelso, 1988; Haken, Kelso, & Bunz, 1985; Zanone & Kelso, 1997).

Based on the above review, there is cause to believe that added variability will assist in breaking away from natural, yet undesired attractors. It has been shown that transitions to new patterns (either as a result of perturbations, a change in constraints such as increased speed, or learning) are preceded by increased variability in the current level of performance (e.g., Haken *et al.*, 1985; Zanone & Kelso, 1992). Therefore, benefits to learning in terms of breaking away from attractors, created from this natural unintentional variability, could be enhanced by adding non-task related variability to the skill during practice.

In the following two experiments we created non-task related variability by adding small mechanical perturbations at various times during a movement trial, which served to knock a person's arm out of their current phase of coordination. In the first experiment we compared two groups, one group received mechanically-induced perturbations to one of their arms after a period of stabilization. As alluded to above (Shea & Wulf, 2005), variability in practice was expected to be beneficial for retention only if it is given later in practice, once the general idea of the movement has been acquired and somewhat stabilized. This non-task related variability was expected to create a general type of interference impacting physically on skill production, providing a greater experience of the perceptual-motor workspace, as well as cognitively, requiring corrections to errors and enhanced cognitive effort. These processes are expected to aid retention. In a second experiment, variability was added throughout practice. Because there is reason to believe that variability early in skill acquisition is desirable for breaking away from undesired movements and acquiring novel movement patterns or phase relations (see Hodges & Franks, 2002) we expected to see a faster rate of acquisition among participants who received this type of training, in addition to benefits in the long-term retention of this skill as compared to no added variability controls.

2.2 Experiment 1

2.2.1 Methods

2.2.1.1 Participants and groups

Eighteen participants were tested (14 females and 4 males, M = 21.3 years, and *SD* = 4.1 years) who were all right-handed, both self-declared and evaluated by the Edinburgh Handedness Questionnaire (Oldfield, 1971). They were pseudo-randomly assigned into 2 groups, Perturbation and Control (no perturbation) groups, controlling for gender across groups. Participants were recruited from the University of British Columbia community and were remunerated $8 per hour. The study was conducted in accordance with the ethical guidelines of the University of British Columbia.

2.2.1.2 Task and apparatus

The task was to learn a bimanual 90° relative phase pattern. Participants were instructed to constrain their movement to a peak to peak, from maximum flexion to extension, amplitude range of approximately 40° as dictated by markers attached to the tabletop. The task goal was specified by a real time displacement-displacement plot of the right-limb against the left-limb, forming what is referred to as a Lissajous plot (e.g., Hodges & Franks, 2002). When performing the correct 90° RP pattern a circle trace is formed and hence the task goal is represented by the completion of approximately one circle per second, during a 20 second trial.

Participants sat in a chair with their arms resting on a manipulanda (52.5 cm in length) with their hands resting on adjustable hand platforms in the pronate position (see Figure 2.1). Adjustments were made such that the elbow joint aligned with the axis of rotation of the manipulanda. Angular movement of the elbow joint in the horizontal plane was manipulated using two DC Torque motors (Mavilor MT-600) and a motion control card (Tech-80 model 5638) in order to administer small perturbations to the limbs. The perturbations were generated by the torque motors using a dampening value of 200 units on the servo card. The resulting viscous field is similar to the experience of moving through a thick liquid, with the forces acting to oppose the direction of movement for 2 seconds. Measurement of angular rotation was captured using an optical encoder (resolution 60,000 counts per revolution, or 0.006 degrees per bit).

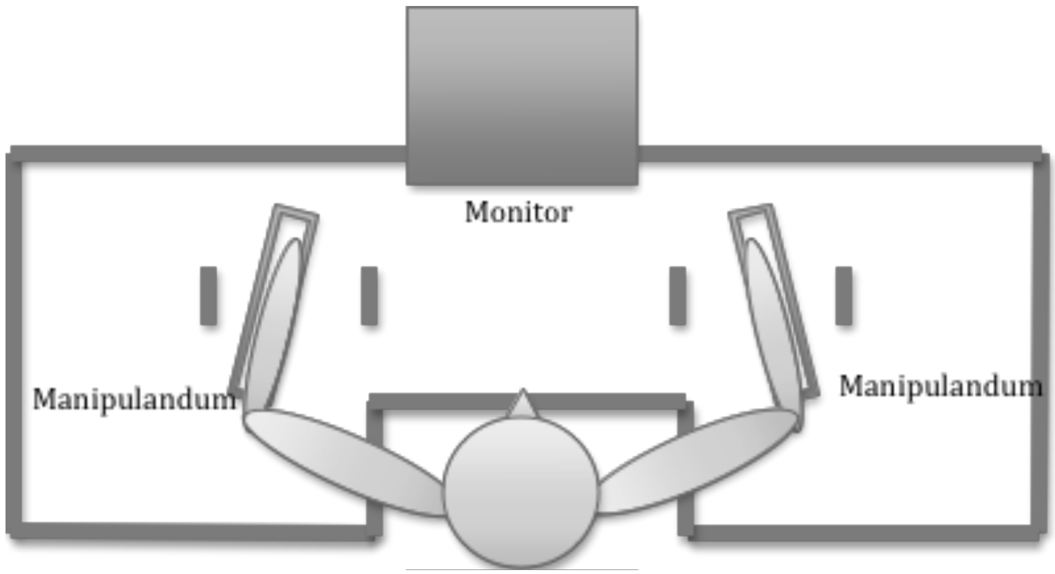

Figure 2.1. Experimental setup showing a participant with arms on the manipulanda looking at the computer monitor.

2.2.1.3 Procedure

The experiment took place over 2 sessions 24 hours apart (for an outline of procedures see Table 2.1). Day 1 began with completion of the consent form and instructions for the task. Participants were given six trials (at 0° and 180° RP) to familiarize themselves with the task. This was to ensure that amplitude and fluidity goals were achieved.

Table 2.1. Experiment 1: conditions and their associated manipulations.

Day	Condition	# of trials	Stimulus	KR	Perturbations
1	Familiarization	6	Lissajous	No	none
	Discrete Scan	12	Pendula	No	none
	Practice Block	40	Lissajous	Yes	none
	Practice Block	40	Lissajous	Yes	4 out of 5*
2	Retention (No Stim)	3	None	No	none
	Retention w feedback	3	Lissajous	No	none
	Perturbation Left	3	Lissajous	No	Yes
	Discrete Scan	12	Pendula	No	none

* Only the Perturbation group received perturbations, the Control group received none.

2.2.1.3.1 Pre and post scans of bimanual coordination abilities

Before practice began, participants performed a 12 trial pre-test scan. This consisted of three trials at four different relative phase patterns (i.e., 0°, 90°, 180° and 270° RP). Each trial lasted 20 seconds and inverted pendula were used to dictate the required relative phase. The pendula were two green vertical lines that oscillated at 1 Hz. These were presented on a computer monitor (40.5cm x 30.5cm, Viewsonic G810) and via manipulations to the time lags between the two pendula it was possible to specify a number of different relative phase relations. Participants were required to track the left and right pendula with their arms. These trials were presented in a pseudo-random order, constrained that the same pattern was not presented twice in a row. A second scan was performed at the end of testing on day 2.

2.2.1.3.2 Practice and experimental manipulations

Practice consisted of 80 trials at the 90° RP pattern (with the right hand leading) with a 5 minute break halfway through testing. All practice trials lasted 20 seconds and included knowledge of results (KR) as well as Lissajous feedback. Terminal knowledge of results was visually displayed, numerically, on the computer screen at the end of each trial in terms of mean constant error (*CE*) and standard deviation (*SD*). Participants were explained that these numbers represented overall trial accuracy (*CE*) and consistency (*SD*). It was also explained that they should try to get these numbers as close to zero as possible, and that they should focus on becoming accurate (*CE*) before consistent (*SD*). The number of trials and the type of feedback were chosen such that both groups would be expected to be able to perform the required movement after a relatively short number of practice trials and, as a result, allow for the evaluation of the strength of learning in retention and transfer tests. This is important as the difference between performing better during practice and a persistent change in the ability to perform, what we call 'learning', are not thought to be correlated or necessarily have shared mechanisms.

Lissajous feedback consisted of a circular template projected on the computer screen. Feedback from the participants' movement was superimposed over the template (60 Hz refresh rate), which showed the participant's current position and the previous 66.7 ms (1/15th of a second) of movement in a real-time, orthogonal displacement-displacement plot of the two limbs. The left manipulandum produced vertical movements of the on-screen cursor and the right manipulandum produced horizontal movements of the on-screen cursor. A tracer line moving around the Lissajous figure at 1 Hz frequency gave timing during the Lissajous trials. The tracer line was 1/40th of the Lissajous figure in length.

During practice the Perturbation group experienced mechanical perturbations to movements of their right arm. Perturbations were only administered in the second half of practice (last 40 trials) for the Perturbation group and not at all for the practice only Control group.

Perturbations were applied three times during each 20-second trial. They lasted for a 1-second duration and they were pseudo-randomly administered, with the constraint that perturbations would randomly begin within 4 to 7 seconds of each other (to allow participants time to recover). As well, perturbations would not begin during the first 2 seconds of the trial (to allow the participant to begin moving), nor during the last 2 seconds of the trial (again, to allow participant time to recover). During practice, perturbations were only applied on 80% of the trials, pseudo-randomly scheduled such that 1 in 5 trials were without perturbations, what we referred to as criterion trials. These criterion trials allowed us to make comparisons in practice with the no perturbation Control group. Participants were not told whether a trial would include perturbations or when the perturbations would be applied within a trial.

2.2.1.3.3 Post-tests (retention and transfer assessment)

Post-tests were conducted 24 hours after practice was completed, and consisted of three conditions (see Table 2.1). No augmented feedback was given (i.e., KR or Lissajous feedback) and all tests were performed at 1 Hz. Three retention tests of the 90° pattern were performed with no visual assistance (i.e., no pendula stimulus), to get an indication of how well the 90° pattern was learned and retained. This same test was then performed with Lissajous feedback. There then followed 3 trials of the 90° pattern with perturbations applied to the left hand (and with Lissajous feedback). Participants then completed the same scanning trials that were administered during the pre-test. At the end of the study participants were debriefed.

2.2.1.3.4 Data analysis

For data analysis purposes, the first and last 2 seconds of each trial were not used. This allowed for more accurate measurement of relative phase as the movement was already underway, or not near completion. Data were collected at 500 Hz, and relative phase (RP) was calculated at 100 Hz (or every $1/5^{th}$ point). Relative phase was calculated by first calculating the phase angle for each hand independently. Given a single data point's position and instantaneous velocity we used the arcsine function to calculate the phase angle for that point. Then, to get a relative phase value, we subtracted the left hand phase angle from the right hand phase angle. Therefore, if the hands were moving in mirror image to each other the phase values would be identical and we would get a value of 0^o RP. Alternatively, if the hands were moving together (like windshield wipers) their difference would be 180^o RP. Using these data, we calculated absolute constant error for each individual trial (i.e., observed RP minus required RP to get constant error and then the unsigned value was used for analysis). We also calculated variable error within the trial (i.e., *SD* of constant error). These two measures gave independent indications of the accuracy and consistency of the movement. A combined measure was also calculated to give an overall measure of performance, what has been referred to as root-mean-square error (*RMS*, see for example, Fontaine, Lee & Swinnen, 1997). Finally, for retention data only, we calculated time spent at different relative phase plateaus within a trial (i.e., within 30 degrees of 0^o, 90^o, 180^o and 270^o, where these values represent the midpoint of the bin).

2.2.1.3.5 Statistical analysis

2.2.1.3.5.1 Practice

Practice data were analyzed in a 2 Group x 2 Condition (First Half and Second Half) x 8 Block repeated measures ANOVA. Separate analyses were conducted on the criterion trials (given once every 5 trials in the second half of practice) for both groups in order to assess performance in the absence of the induced perturbation. These data were analyzed in a 2 Group x 8 Trial repeated measures ANOVA.

2.2.1.3.5.2 Pre and post scans

The two groups were compared in a 2 Group x 2 Day x 4 Plateau repeated measures ANOVA focusing on 0°, 90°, 180°, and 270° relative phase patterns.

2.2.1.3.5.3 Retention and transfer

The two groups were compared in a 2 Group x 2 Feedback Type (no stimulus and Lissajous feedback) repeated measures ANOVA. Comparisons were also made across the two groups using a 2 Group x 2 Test repeated measures ANOVA to compare the left arm perturbation (with Lissajous feedback) to the Lissajous feedback retention test. For each retention trial, we also calculated the time spent at 4 relative phase bins within a trial (0°, 90°, 180°, and 270° RP). This resulted in a 2 Group x 2 (Feedback Type) x 4 RP bin repeated measures ANOVA for this measure.

Effect size measures (partial eta squared, η_p^2) are reported for all statistically significant effects and power calculations (β) for non-significant effects. When there were violations to sphericity for repeated measures values (typically for Block and Trial), the Greenhouse Geiser correction factor was used (based on adjusted *df*).

2.2.2 Results

2.2.2.1 Practice

The *RMS* data as a function of condition and block is shown in Figure 2.2. Both groups improved during the acquisition period, that is they performed with reduced error (RMS) as indicated by a main effect of block, $F(2.5,40.6)= 55.99$, $MS_e = 145.08$, $p < 0.001$, $\eta_p^2 = 0.78$. The addition of random perturbations in the second half of practice increased overall (*RMS*) error as indicated by a main effect for group, $F(1,16) = 12.52$, $MS_e = 322.10$, $p < 0.01$, $\eta_p^2 = 0.44$, as well as by a Group x Condition interaction, $F(1,16) = 5.57$, $MS_e = 252.16$, $p = 0.031$, $\eta_p^2 = 0.26$. As can be seen in Figure 2.3, the Perturbation group increased their error during the second part of practice. This was due to a large increase in the variable error (*SD*) for the group receiving perturbations in the second half of practice as indicated by the Group x Condition interaction for this metric, $F(1,16)= 10.86$, $MS_e = 120.83$, $p < 0.01$, $\eta_p^2 = 0.40$. Therefore, the manipulation had its intended effect. No other group related effects were observed for any of the measures.

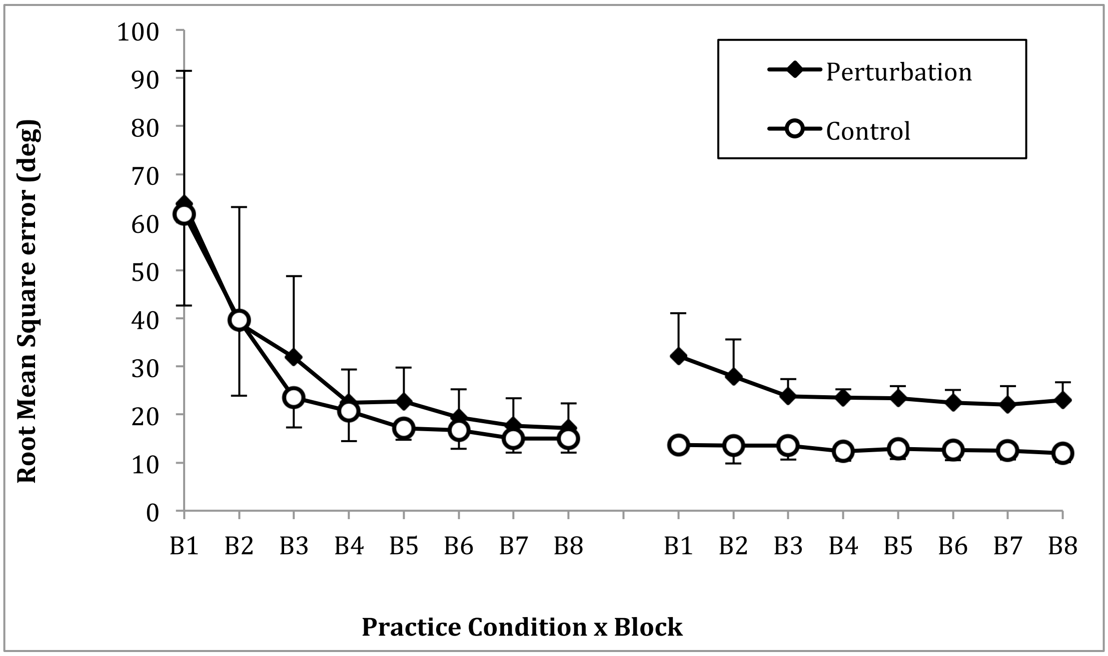

Figure 2.2. Experiment 1: *RMS* error across Practice Condition and Block. Error bars are *SD*.

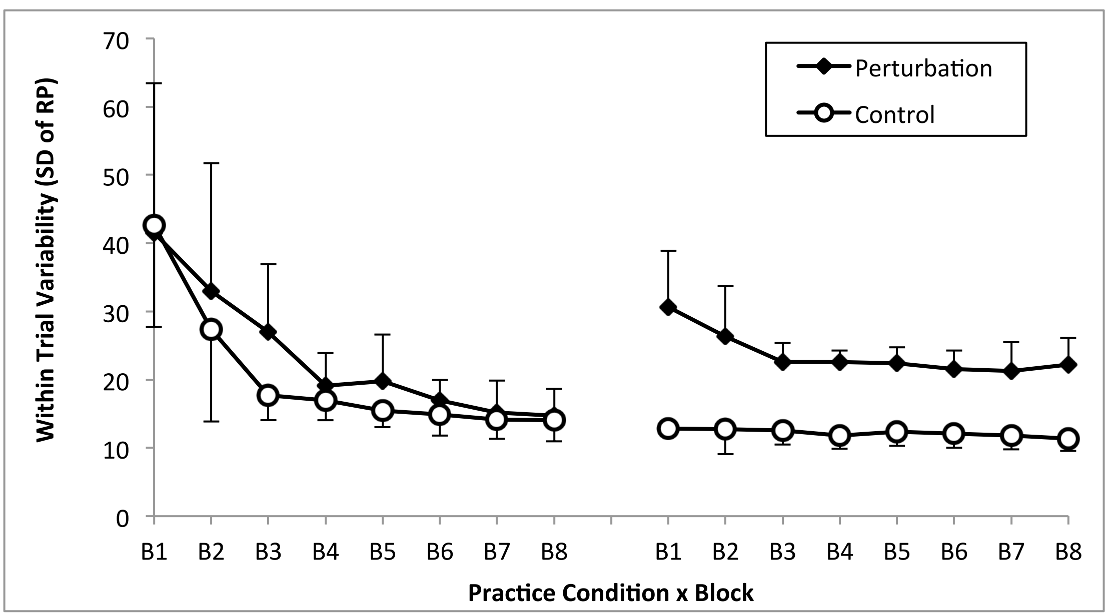

Figure 2.3. Experiment 1: within Trial variability (*SD)* error across Practice Condition and Block. Error bars are SD.

We also analyzed performance on criterion trials (i.e., no perturbation trials) for the perturbation group in the second half of practice. These were compared to matched trials for the control group. For our overall measure of performance (*RMS*) there was no Group, $F(1,16)= 1.44$, $MS_e = 45.68$, $p = 0.25$, $\beta = .204$ nor Trial, $F(7,112)= 1.64$, $MS_e = 7.76$, $p = 0.13$, $\beta = .65$ effect, and no interaction, $F < 1$. However, inspection of *ACE* showed that the Control group was more accurate ($M = 3.04^o$, $SD = 2.03^o$) than the Perturbation group ($M = 5.96^o$, $SD = 5.07^o$) on these trials, despite the fact that neither group was receiving perturbations, $F(1,16)= 4.40$, $MS_e = 69.73$, $p = 0.052$, $\eta_p^2 = 0.22$, $\beta = .504$. There was no Group x Trial interaction for *ACE*, $F(3.7, 59.7) = 1.39$, $\beta = .39$. No differences in variability were observed, opposite to what we saw in the non-criterion trials. Although the perturbation group performed with more variability during the intervention, when this manipulation was removed the participants did not continue to show increased variability relative to the Control group, but they were more errorful.

2.2.2.2 Pre and post scans

As expected, both the Perturbation and Control groups reduced *RMS* error from pretest ($M = 58.70^o$, $SD = 38.88^o$) to posttest ($M = 53.07^o$, $SD = 40.06^o$), $F(1,16) = 15.47$, $MS_e = 73.87$, $p < 0.001$, $\eta_p^2 = 0.49$. There was not a reduction in accuracy (*ACE*), $F < 1$, only in variability (*SD*), $F(1,16) = 18.26$, $MS_e = 109.96$, $p < 0.001$, $\eta_p^2 = 0.53$. There was also a main effect of RP Plateau for *RMS*, $F(1.62,25.85) = 96.79$, $MS_e = 1106.28$, $p < 0.001$, $\eta_p^2 = 0.89$. As would be expected, 0° and 180° were performed with less error than 90° and 270°, but there was no Day x RP plateau interaction ($F(1.79,28.57) = 2.15$, $\beta = .38$ see Figure 2.4).

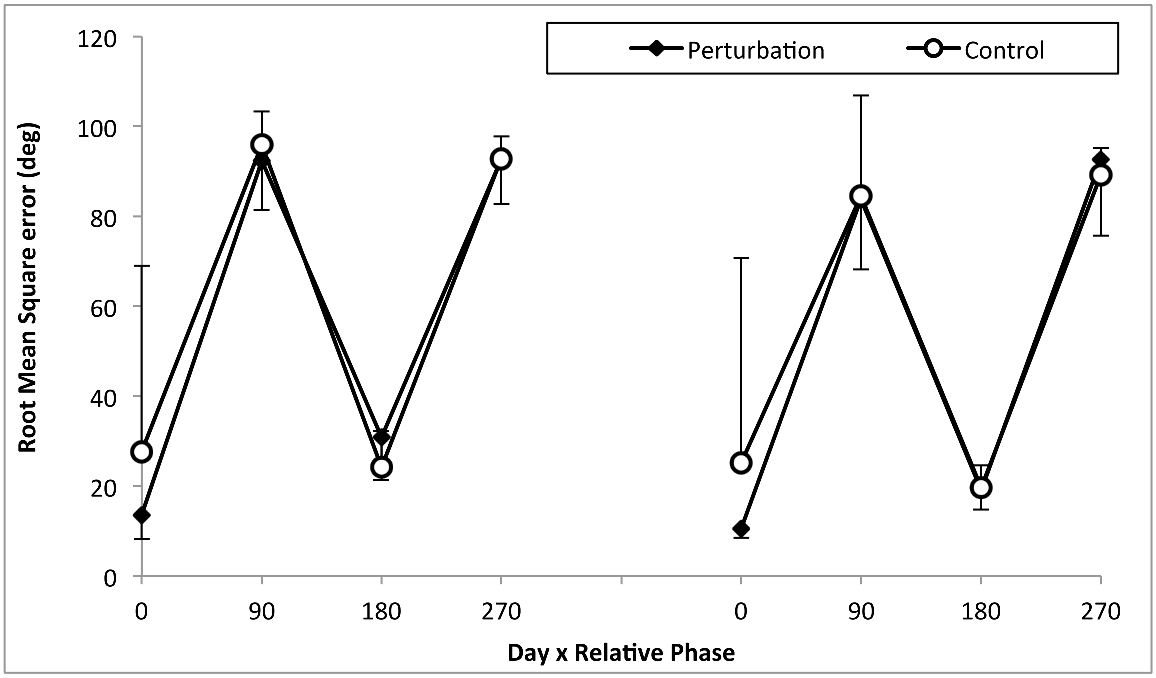

Figure 2.4. Experiment 1: Pre and Post test scanning results for the 4 relative phase plateaus (0°, 90 °, 180°, and 270°) showing *RMS* error. Error bars are *SD*.

Despite our predictions, there was no main effect for group, nor any interactions involving group for *RMS*. The only interaction that was significant was for *SD*, and this was due to a cubic trend for the Group x Day x Plateau interaction, $F(1,16) = 4.94$, $MS_e = 76.68$, $p = 0.041$, $\eta_p^2 = 0.24$. We have plotted these data in Figure 2.5, where it can be seen that the Control group showed a decrease in variability at the two intermediate patterns of 90° and 270° RP.

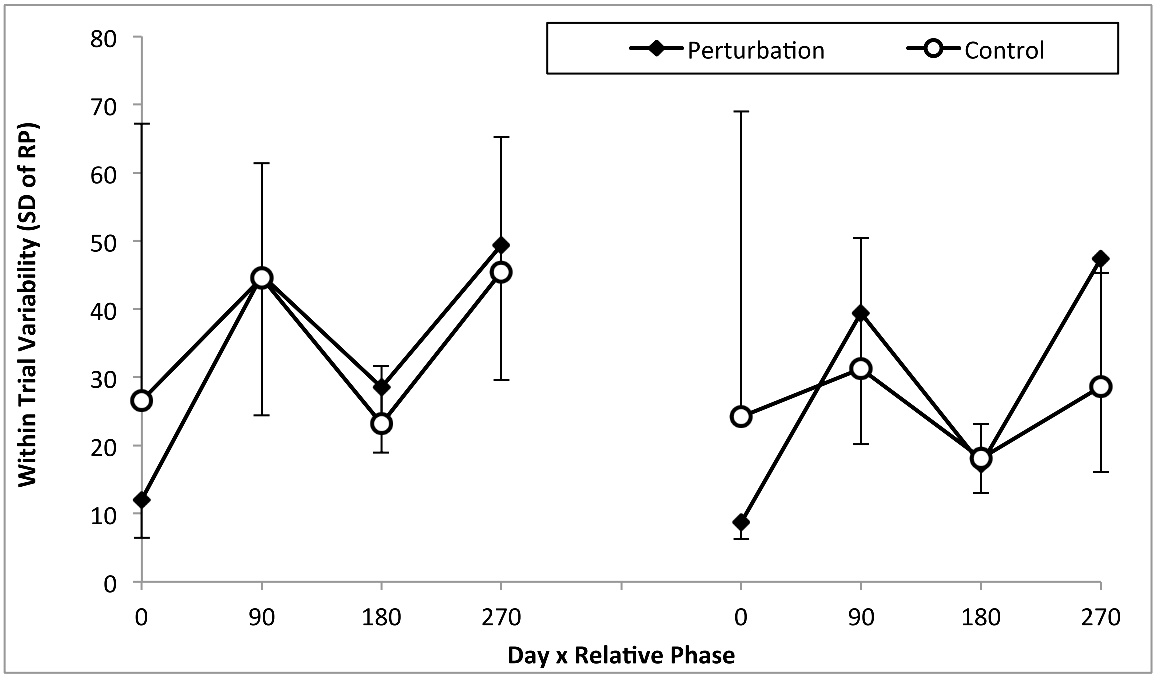

Figure 2.5. Experiment 1: Pre and Post test scanning results for the 4 relative phase plateaus (0°, 90°, 180°, and 270°) showing within trial variability (*SD*) error. Error bars are *SD*.

2.2.2.3 Retention and transfer

As expected, both groups performed better during retention when they received Lissajous feedback (M_{RMS} = 15.71°, *SD* = 4.21°) compared to when they had no feedback, that is the no stimulus condition (M_{RMS} = 63.24°, *SD* = 30.71°), *RMS*, $F(1,16) = 45.82$, MS_e = 443.75, $p < 0.001$, $\eta_p^2 = 0.74$. This effect was also seen for *ACE* and *SD* (both *ps* < 0.001). Contrary to our predictions, there was no effect of group, nor any group interactions in any of our measures, including analysis of time spent at various RP bins within a trial, *Fs* < 1 (see Figure 2.7 for retention and transfer results). For this latter analysis, there was evidence that participants were spending time around the 90 degree relative phase plateau, in both groups, but this was most evident when Lissajous feedback was available as evidenced by a Feedback x Relative Phase Plateau interaction, $F(1.91,30.49) = 48.80$, $MS_e = 8.59$, $p < 0.001$, $\eta_p^2 = 0.75$ (see Figure 2.6).

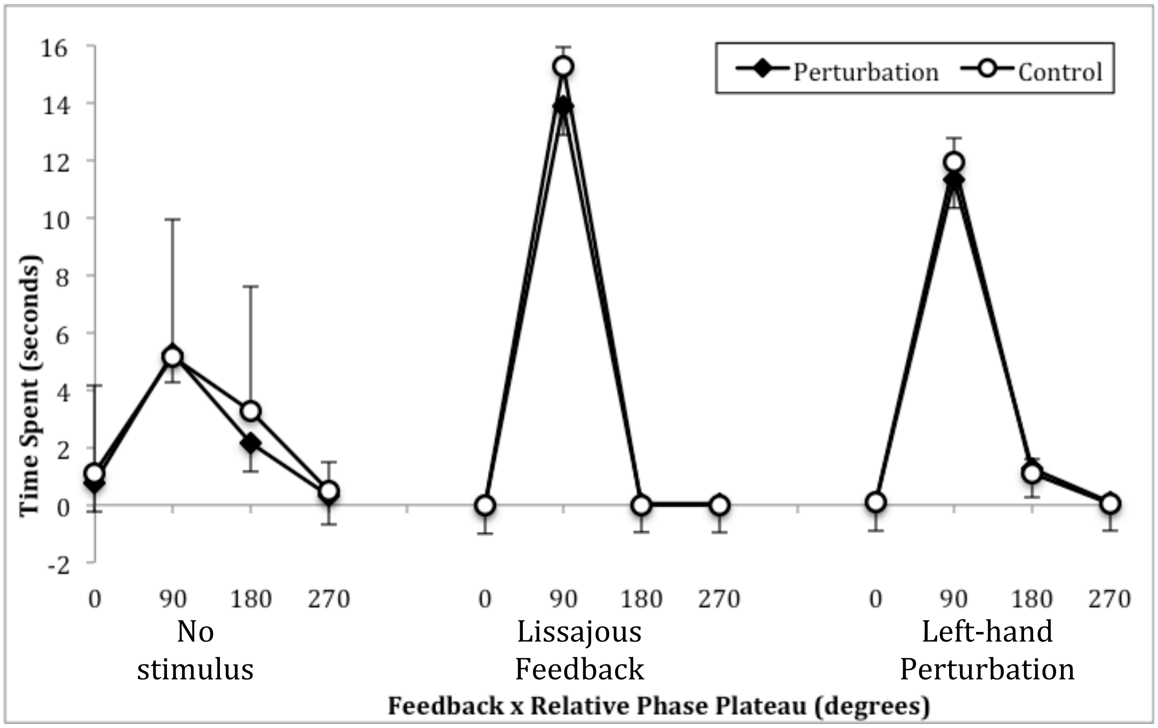

Figure 2.6. Experiment 1: No stimulus retention, Lissajous feedback retention, and Left-hand Perturbation transfer results, showing time spent in seconds around each relative phase plateau (degrees). Error bars are SD.

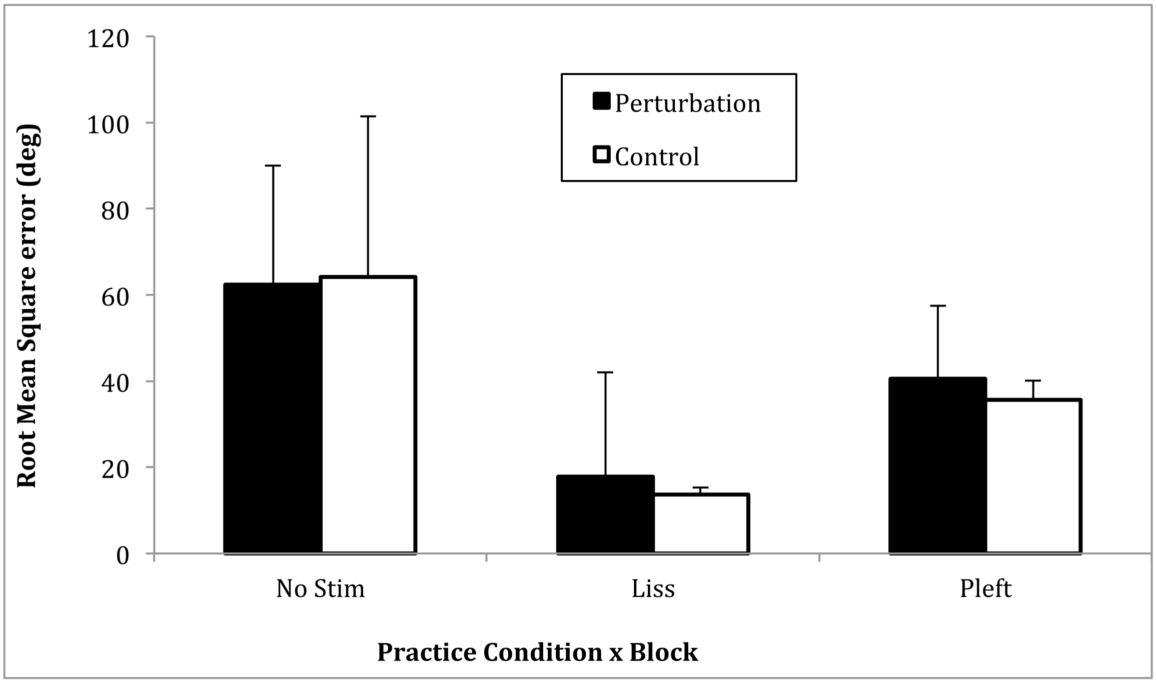

Figure 2.7. Experiment 1: Post test retention and transfer results for all 3 conditions, showing *RMS* error. Error bars are *SD*.

Comparison of the left-hand perturbation condition to the retention test for RMS yielded a main effect of group, $F(1,16) = 7.09$, $MS_e = 26.46$, $p = .017$, $\eta_p^2 = 0.31$, test condition, $F(1,16) = 140.52$, $MS_e = 32.04$, $p = 0.011$, $\eta_p^2 = 0.90$, but no Group x Test interaction, $F < 1$. The Control group showed less error overall on both tests, even though both groups showed an increase in error on the left-hand perturbation test. These differences were mainly a result of decreased variability for the Control group in comparison to the Perturbation group ($p < 0.05$), as well as reduced variability and accuracy in retention conditions as compared to the perturbation conditions (*ps* < 0.05). The analysis of time-spent at various relative phase plateaus also failed to show any group differences.

2.2.3 Discussion

In this experiment we compared two groups of participants who practiced a novel phase relation between their hands with non-task related variability added later in practice for one of the groups. This Perturbation group was compared to a non-perturbation Control group during practice on non-perturbation and perturbation trials, as well as on retention and transfer tests. We expected that variability introduced late in practice would aid retention.

As we expected, the mechanical perturbations did increase variability (i.e., within trial *SD*) of the Perturbation group in the second half of practice when perturbations were administered. Also, our procedures were successful in teaching this new pattern to the participants, as evidenced by reduced error during the acquisition phase for both groups and in scanning tests showing a general reduction in error for both groups pre and post-practice (although there was no Day x Plateau interaction which would suggest more error reduction at the 90^o and 270^o RP patterns). Although both groups showed low error in the retention tests, especially when Lissajous feedback was provided, contrary to our expectations, the Perturbation group did not perform with less error than the Control group in any of the retention or transfer tests. In contrast, the Control group showed a trend to perform better in the retention tests when feedback was provided, even in the face of added variability (i.e., left hand perturbations). Therefore, externally added, non-task related variability in practice does not facilitate learning and might even be detrimental (*cf.*, Schollhorn *et al.*, 2006).

Although it is possible that this type of added variability is not a useful practice technique, at least for the acquisition and retention of a new coordination movement, there were three methodological concerns with this experiment that prevented us from making this conclusion. These concerns are related to the type and amount of feedback provided, the amount of practice, and the decision to administer perturbations (i.e., bring variability into the practice environment) only later in practice.

Lissajous feedback has been shown to be a significant guiding source of information for learning tasks of this nature (e.g., Maslovat *et al.*, 2010; Hodges & Franks, 2000, 2001; Kovacs & Shea, 2011). When it is removed, participants often show little evidence of learning (i.e., that the movement pattern has been internalized, Zanone & Kelso, 1997). Further, when it is available it significantly eases performance such that researchers have recently suggested that movement patterns that lie intermediate to 0^{o} and 180^{o} RP are not learnt, but merely stabilized with the appropriate feedback. For example, Kovacs *et al.* (2009) found that with Lissajous feedback, within 5 minutes, people were able to perform a variety of RP patterns without any practice. Therefore, it is possible that the type of feedback we provided both made the task too easy when it was available, preventing the detection of group differences, as well as making the task too difficult when it was withheld. There was significant evidence that participants in our study were heavily reliant on the Lissajous feedback for performance, as evidenced by the significant increase in error when it was unavailable in retention. Indeed, the variability in performance when feedback was unavailable was similar to that observed under the left-hand, external perturbation conditions where variability was forced. Indirectly, this indicates that the Lissajous feedback serves to limit variability in general, possibly moderating the effects of any type of perturbation.

A second factor to be considered with this manipulation was the duration of the practice session in conjunction with the feedback. In this experiment, due to the fact that participants were able to acquire the required phasing relatively quickly in practice, we decided to limit practice to one day and provide the perturbations after an initial period of acquisition. It is possible, especially if Lissajous feedback is reduced, that more practice trials or practice distributed over a couple of days would help the stability of the acquired movement pattern and potentially decrease the reliance on Lissajous feedback.

Related to this point, in this experiment, we had decided to administer the perturbations only after the participants had received practice and had arguably acquired the movement pattern. This was evidenced by a significant decrease in error over the first half of practice for both groups. In previous research, there has been evidence that task related variability is most useful once a person has had a period of practice under constant practice conditions (see Shea & Wulf, 2005; Albaret & Thon, 1998; Maslovat *et al.*, 2004). Although we did not find that to be the case in this experiment, there is also reason to believe that variability provides a benefit early in acquisition process in order to aid the break away from stable attractors, or unwanted behaviours (Hodges & Franks, 2001, 2002). Moreover, because we restricted our manipulation to only half of the practice trials, it is possible that any potential effects of the manipulation were dissipated, due to the relatively low number of trials when variability was added.

In view of these considerations noted above, we made a number of changes to our protocol in order to further test for the potential benefits of non-task related variability in aiding the acquisition of a new coordination movement. Two groups of participants practiced over 2 days, with retention and transfer tests on a third day. We restricted the amount of Lissajous feedback, and instead presented oscillating pendula on the majority of trials, corresponding to the desired motions of the left and right hand. Perturbations were also given throughout practice (again, interspersing with criterion trials) in order to increase the number of practice trials with this added variability. This also allowed us to determine whether there were any potential benefits to be gained from early variability, potentially speeding up the acquisition process by aiding in breaking away from undesirable, natural attractors of in- and anti-phase.

2.3 Experiment 2

2.3.1 Introduction

In this experiment two groups who either received perturbations throughout a 2-day practice intervention (Perturbation group) or did not receive any perturbations during practice (no perturbation Control group) were compared. If added variability in practice, in the form of mechanical perturbations, serves to aid performance and learning, then we would expect to see that the Perturbation group acquires the desired movement (i.e., 90° RP) more quickly than the Control group and shows more stable (and accurate) performance when tested in a delayed retention test.

In addition to examining performance of this newly acquired motor pattern in retention, we also used a transfer test in this experiment that was designed to bring about increased variability in the movement in the form of increased stress or anxiety. We were interested to see whether the addition of externally-added variability during practice phase acts to ward off negative consequences associated with stressors perceived or induced during a later test phase. An important characteristic of motor skills, particularly in sporting domains, is resilience to competitive stress (Van Gemmert & Van Galen, 1998). Van Gemmert and Van Galen (1997) proposed that both physical and mental stressors share a common mechanism, where both types of stressors increase the level of neuromotor noise or variability. If participants are accustomed to performing with additional variability during practice, then it is reasonable to expect that people who practice in a higher variability environment should more readily compensate for additional variability in the system derived from external stressors.

2.3.2 Methods

2.3.2.1 Participants and groups

Twenty new participants were tested, 12 females and 8 males, (*M* = 21.8 years, and *SD* = 3.2 years) who were all right-handed, both self-declared and evaluated by the Edinburgh Handedness Questionnaire (Oldfield, 1971). They were pseudo-randomly assigned into 2 groups, Perturbation and Control (no perturbation) groups, approximately controlling for gender. Participants were recruited from the University of British Columbia community and were remunerated $8 per hour. The study was conducted in accordance with the ethical guidelines of the University of British Columbia.

2.3.2.2 Task and apparatus

These were the same as Experiment 1 except the task goal was specified by two moving inverted pendula presented on a computer monitor (40.5cm x 30.5cm, Viewsonic G810) situated 65.5 cm in front of the participant. The pendula were green vertical lines that oscillated from 0.75 Hz to 1 Hz. Manipulations to the time lags between the pendula allowed for presentation of different relative phase relations when required. Participants were required to track the left and right pendula with their arms that were attached to the moving platforms.

2.3.2.3 Procedure

The experiment took place on 3 separate days, over an 8-day period (for an outline of procedures see Table 2.2). Day 1 began with completion of the consent form and instructions for the task. Participants were given six trials (at 0° and 180° RP) to familiarize themselves with the task. This was to ensure that amplitude and fluidity goals were achieved.

Table 2.2. Experiment 2: conditions and their associated manipulations.

Day	*Condition*	*# of trials*	*Stimulus*	*KR*	*Frequency*	*Perturbations*
1	Familiarization	6	Lissajous	No	1	none
	Discrete Scan	12	Pendula	No	1	none
	Practice	20	Pendula	Yes	0.75	4 out of 5*
	Practice	5	Lissajous	Yes	0.75	4 out of 5*
	Practice	20	Pendula	Yes	0.85	4 out of 5*
	Practice	5	Lissajous	Yes	0.85	4 out of 5*
	Practice	30	Pendula	Yes	1	4 out of 5*
2	Practice	20	Pendula	Yes	0.85	4 out of 5*
	Practice	5	Lissajous	Yes	0.85	4 out of 5*
	Practice	55	Pendula	Yes	1	4 out of 5*
3	Retention	3	No Stimulus	No	1	none
	Faded Stimulus	3	Lissajous	No	1	none
	Discrete Scan	12	Pendula	No	1	none
	Perturbation	6	Pendula	No	1	Left and Right
	Stress	4	No Stimulus	No	2	none

* Only the Perturbation group received perturbations, the Control group received none.

2.3.2.3.1 Pre and post scans of bimanual coordination abilities

Participants performed a 12 trial pre-test scan (see Experiment 1). An additional scan was performed at the end of day-3.

2.3.2.3.2 Practice and experimental manipulations

Practice consisted of 160 trials at the 90° relative phase pattern (with the right hand leading) spread over 2-days (80 trials per day), spaced 24-hours apart. Visual feedback of the limbs was occluded during practice via a black felt sheet placed over the participants' arms and manipulanda. Verbal feedback was given if the desired amplitude was not achieved. As detailed above, the task goal was specified by moving inverted pendula. All practice trials lasted 20 seconds and knowledge of results (KR) was again provided at the end of the trial, as with Experiment 1.

To facilitate learning during practice, speed of movement and feedback were manipulated (see Maslovat *et al.*, 2010 who used a similar procedure). Stimulus frequency, shown by the frequency of the pendula itself, began reduced and gradually increased such that, on day-1, participants performed 25 trials at 0.75 Hz, then increased to a rate of 0.85 Hz for 25 trials. Day-1 ended with 30 trials at the criterion speed of 1 Hz. Day-2 started with 25 trials at 0.85 Hz and followed with 55 trials at the criterion speed, 1Hz. Lissajous feedback was sparingly provided in this experiment, such that it replaced pendula stimulus for three blocks of practice (15 trials). This feedback was provided on trials 21 to 25 and 46 to 50 on day-1; and, on trials 21 to 25 on day-2.

During practice the Perturbation group experienced perturbations to movements of their right arm. Different to Experiment 1, these perturbations were administered throughout practice. Although, as with the first experiment, we continued to include no perturbation criterion trials (1 out of 5 trials) in order to allow comparisons during practice across the two groups.

2.3.2.3.3 Post-tests (retention and transfer assessment)

Day-3 was delayed 6-days from practice on day-2, and consisted of five post-test conditions (see Table 2.2). No augmented feedback was given and all were performed at 1 Hz. To begin, three retention tests of the 90° pattern were performed with no visual assistance (i.e., no pendula stimulus) to get an indication of how well the learned pattern was remembered and retained. Another measure of learning used in retention were three 20-second trials, requiring performance of the 90° RP pattern where the tracking stimulus (i.e., pendula) disappeared from the computer screen after five-seconds. The participant was required to continue the movement in the absence of the visual stimulus. No augmented feedback (knowledge of results) was given during these trials. Participants then completed the same 12-trial post-scan as the pre-test, followed by 6 trials with perturbations administered to either their right (as was the case in practice) or their left arm. Participants were unaware whether the trial would consist of left or right arm perturbations. The schedule was pseudo-random, such that all three trials for one arm would not occur consecutively. Finally, participants performed 3 trials under conditions designed to increase stress. They were instructed that in this condition there was an opportunity to earn extra performance based remuneration. In addition, an external observer was also brought in during these trials to ask questions between trials and evaluate performance. The task was still to perform a 90° RP pattern at 1 Hz with no visual stimulus for these trials. At the end of the study participants completed the Edinburgh Handedness questionnaire and were debriefed.

2.3.2.3.4 Data analysis

Data analysis procedures were the same as Experiment 1 and the same dependent measures were calculated and analyzed.

2.3.2.3.5 Statistical analysis

2.3.2.3.5.1 Practice

Practice data were analyzed in a 2 Group x 2 Day x 14 Block repeated measures ANOVA (due to Lissajous feedback, blocks 5 and 10 on each day were excluded from analysis). Separate analyses were conducted on the criterion trials (given once every 5 trials). These data were analyzed in a 2 Group x 2 Day x 14 Trial repeated measures ANOVA.

2.3.2.3.5.2 Pre and post scans

The two groups were compared in a 2 Group x 2 Day x 4 Plateau (0°, 90°, 180°, and 270° RP) repeated measures ANOVA.

2.3.2.3.5.3 Retention and Transfer

The two groups were compared in a 2 Group x 2 Feedback Type (no and faded stimulus) repeated measures ANOVA. A comparable 2 Group x 2 Test (no stimulus and stress) ANOVA was conducted to evaluate the stress condition. Comparisons were also made across the two types of perturbations, left and right in a similar 2 Group x 2 Side (Left and Right) analysis. As with Experiment 1, for each retention trial, we also calculated the time spent at 4 relative phase bins within a trial (0°, 90°, 180°, and 270°). This resulted in a 2 Group x 2 (Feedback Type) x 4 RP bin repeated measures ANOVA for this measure.

2.3.3 Results

2.3.3.1 Practice

As with the first experiment, both groups improved during practice, that is they performed with reduced error (*RMS*) as indicated by a main effect of block, $F(4.9,88.8) = 10.07$, $MS_e = 259.66$, $p < 0.001$, $\eta_p^2 = 0.36$. These data are illustrated in Figure 2.8. However, despite the fact that the Perturbation group received perturbations throughout practice, there was no main effect for Group for this measure, $F(1,18) = 1.01$, $MS_e = 7048.51$, $p = 0.33$, $\beta = 0.16$. Although the Perturbation group ($M_{SD} = 45.64°$, $SD = 16.63°$) had greater variability than the Control group ($M_{SD} = 37.16°$, $SD = 18.94°$), we did not see a statistically significant difference, $F(1,18) = 3.01$, $MS_e = 3337.79$, $p = 0.100$, $\beta = 0.38$ (see Figure 2.9). No other group related effects were significant for either of these measure or for *ACE*.

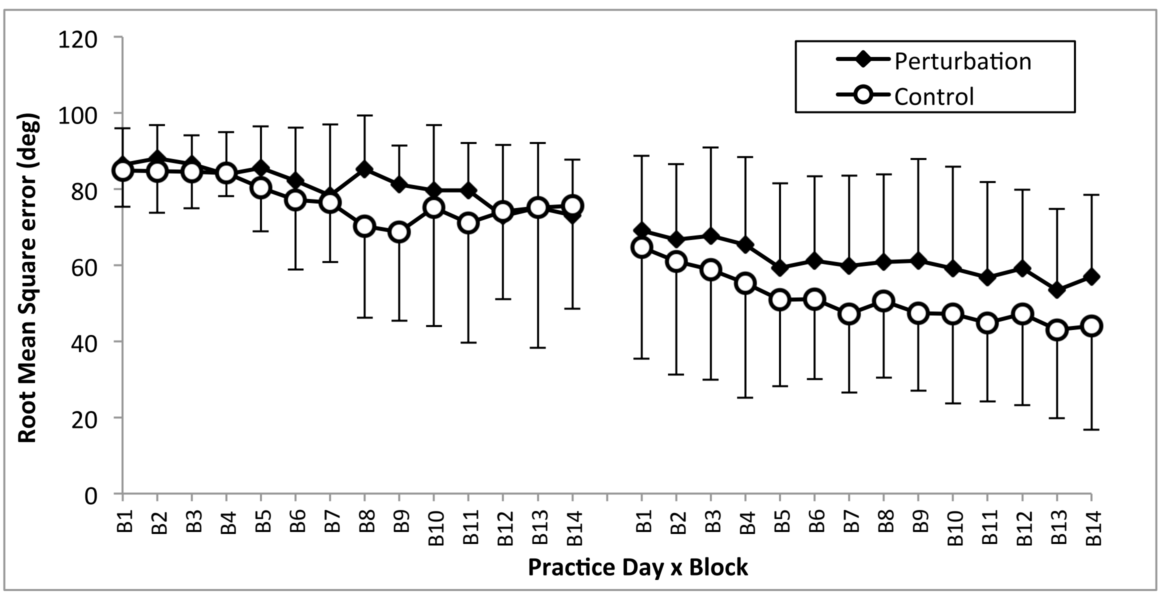

Figure 2.8. Experiment 2: *RMS* error across Practice Condition and Block. Error bars are *SD*.

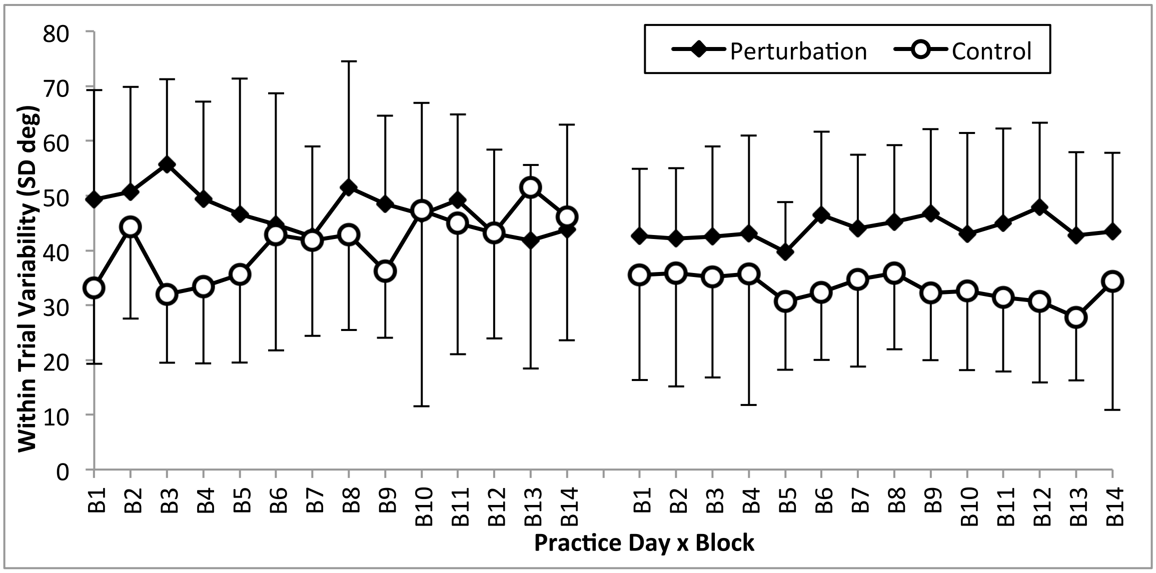

Figure 2.9. Experiment 2: within Trial variability (*SD)* error across Practice Condition and Block. Error bars are *SD.*

We also analyzed performance on criterion trials (i.e., no perturbation trials) for the perturbation group throughout practice. These trials were compared to the average for the same block from the control group. For our overall measure of performance (*RMS*) there was again a main effect of block, $F(6.2,112.2) = 6.80$, $MS_e = 316.81$, $p < 0.001$, $\eta_p^2 = 0.27$ which had a significant linear component ($p = .04$), but no group effect, $F < 1$, nor Group x Block interaction, $F(6.24, 112.2) = 1.06$, $MS_e = 316.81$, $p = .40$, $\beta = .41$. No group related effects were seen in any of our other measures.

2.3.3.2 Pre and post scans

As expected, we saw a main effect for day, showing that the groups reduced overall *RMS* (see Figure 2.10) from pretest ($M = 61.38°$, $SD = 38.69°$) to retention on day 3 ($M = 50.97°$, $SD = 41.14°$), $F(1,18) = 16.14$, $MS_e = 268.98$, $p = 0.001$, $\eta_p^2 = 0.47$ and improved accuracy by reducing *ACE*, $F(1,18) = 21.58$, $MS_e = 218.78$, $p < 0.001$, $\eta_p^2 = 0.55$.

However, there was no reduction in variability (*SD*), $F < 1$, $\beta = .054$. Also, as expected, a main effect of RP plateau for *RMS* was observed, $F(2.26,40.67) = 121.47$, $MS_e = 688.99$, $p < 0.001$, $\eta_p^2 = 0.87$. In general 0° ($M_{RMS} = 14.78°$, $SD = 6.61°$) and 180° RP ($M_{RMS} = 31.41°$, $SD = 25.09°$) were performed with less error than 90° ($M_{RMS} = 78.97°$, $SD = 25.67°$) and 270° RP ($M_{RMS} = 99.54°$, $SD = 19.75°$). There was also a Day x Plateau interaction, $F(2.147,38.646) = 4.76$, $MS_e = 446.58$, $p = 0.013$, $\eta_p^2 = 0.21$. Based on Tukey HSD post hoc comparisons, this was due to reduction of error for the 90° RP pattern on day-3 in comparison to day-1. Similar interaction effects were noted for *ACE* and *SD* (*p*s < .01). No group related effects were seen for any of the measures.

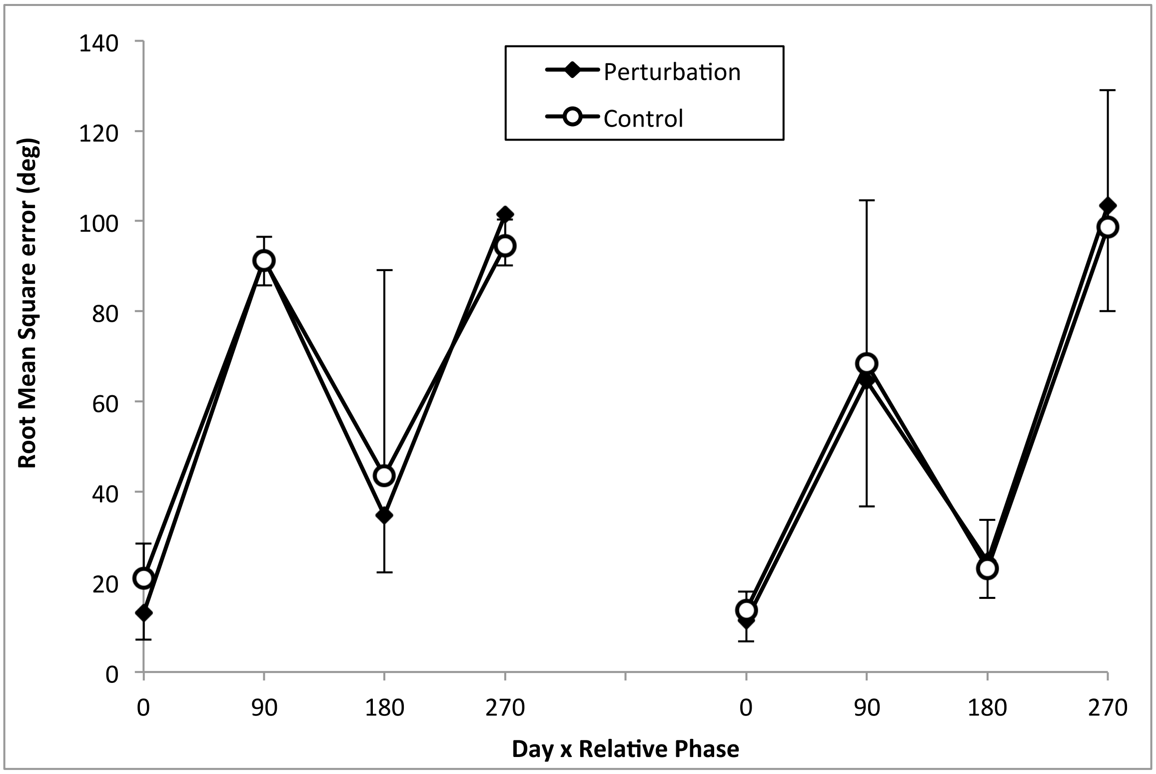

Figure 2.10. Experiment 2: Pre and Post test scanning results for the 4 relative phase plateaus (0^o, 90^o, 180^o, and 270^o) showing *RMS* error. Error bars are *SD*.

2.3.3.3 Retention

We expected that the Perturbation group (M_{RMS} = 55.93°, *SD* = 37.69°) would perform with less error in retention than the Control group (M_{RMS} = 49.50°, *SD* = 33.63°) on both the Faded stimulus and No stimulus tasks, but this was not the case for any of the dependent variables (all *F*s < 1). There was also no effect of Feedback or Group x Feedback interactions, *F*s < 1 (see Figure 2.11 for retention and transfer results).

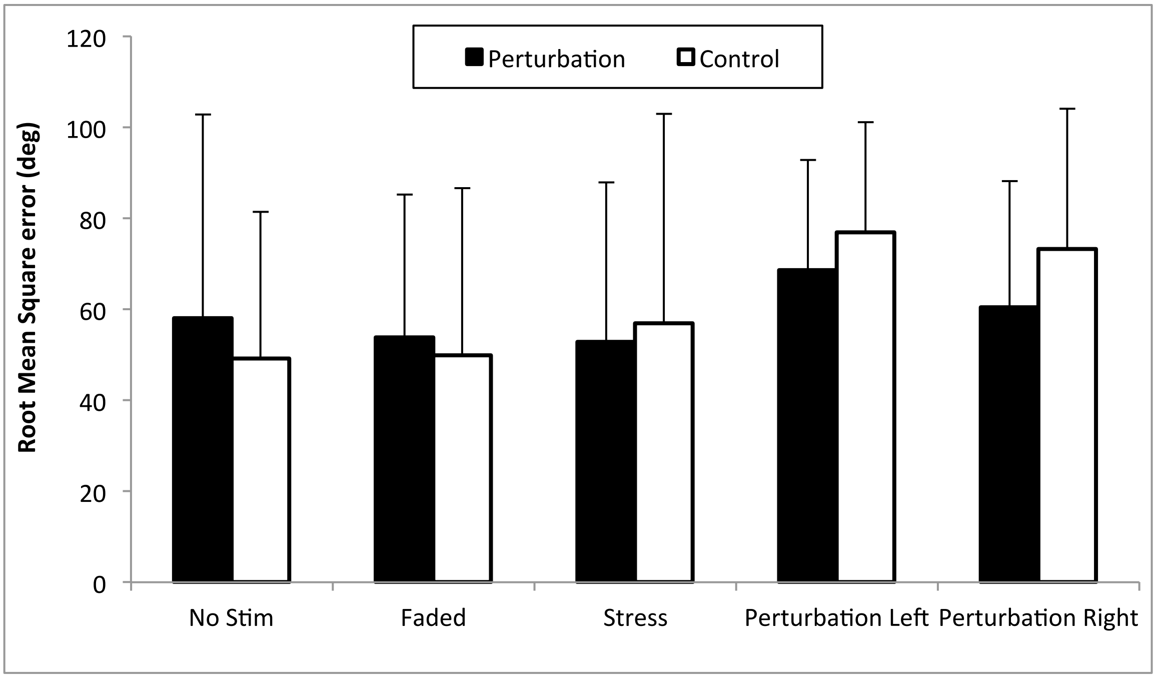

Figure 2.11. Experiment 2: Post test retention and transfer results for all 5 conditions, showing RMS error. Error bars are SD.

2.3.3.4 Transfer

Although the Perturbation group (M_{RMS} = 52.8°, *SD* = 35.0°) performed with less error than the Control group (M_{RMS} = 56.8°, *SD* = 46.2°) under stress-inducing conditions in comparison to no stimulus retention where they performed with more error than the control group, the group effect was not significant ($F < 1$). Also, the test effect was not significant ($F < 1$) neither was the Group x Test interaction, $F(1,18) = 1.39$, $MS_e =$ 292.28, $p = 0.25$, $\beta = 0.20$. None of the other variables showed significant effects.

In our comparison of perturbations to the left hand and right hand, we expected that the Perturbation group would perform with less error than the Control group and that perturbations to the right hand (similar to practice for Perturbation group) would be performed with less error than when to the left hand. Although the Perturbation group was generally less variable (M_{SD} = 46.07°, *SD* = 14.12°) than the Control group (M_{SD} = 55.60°, *SD* = 21.61°) with respect to *SD*, $F(1,18) = 1.589$, $\beta = .223$, there were no differences between the two groups for *RMS* or *ACE* (both *F*s < 1). As expected, perturbations to the right hand (M_{RMS} = 66.86°, *SD* = 29.23°) were performed with less error than to the left hand (M_{RMS} = 72.72°, *SD* = 23.98°), $F(1,18) = 5.10$, $MS_e = 67.39$, p = 0.04, $\eta_p^2 = 0.22$. This was a result of increased variability in the left hand, *SD*, $F(1,18)$ = 10.15, $MS_e = 83.94$, $p < 0.01$, $\eta_p^2 = 0.36$, rather than decreased accuracy (*ACE*, F < 1). However, there was no Group x Hand interaction for any of the measures, time spent, *RMS* and *SD*, *F*s < 1, *ACE*, $F(1,18) = 1.12$, $\beta = 0.17$.

2.3.5 Discussion

In this experiment, as with Experiment 1, we expected to see three key findings. The variability manipulation was expected to increase variability during practice, both groups were expected to show improvements over practice and, most importantly, the groups were expected to be different in retention/transfer, with the Perturbation group showing less error/variability than the Control group.

Against our predictions, and contrary to what we observed in Experiment 1, although the Perturbation group did perform with more variability during acquisition, we did not see a significant increase in variability (*SD*, p = .10) or overall error (*RMS*, p = .33) for the Perturbation group. Therefore, our variability manipulation had diminished effects in this experiment compared to Experiment 1 (we discuss the potential reasons in the General Discussion).

There was evidence that the procedural protocol we had chosen for this task was able to bring about performance improvements and learning as evidenced by an improvement over practice blocks as well as a reduction in error when comparing the post-test scanning trials to the pre-test trials. Furthermore, this improvement was largely due to a reduction in error at the practiced 90^{o} RP pattern, as evidenced by a Day x RP interaction.

Beyond just performance improvements, we expected to find that the Perturbation group would perform with less error than the Control group in retention and transfer tests; however, we found no evidence to support this major hypothesis. When performing with perturbations to the right or left arm in transfer testing, although the Perturbation group was less variable than the Control group, this difference was not statistically significant and there were no differences with respect to accuracy. Similarly, a non-significant advantage was also noted for the Perturbation group under the stress conditions, where there was less overall error (*RMS*) for the Perturbation group in comparison to the Control group, when comparing across the no stimuli retention and stress tests. These were the only slight advantages associated with this method of practice and, hence, we would be cautious in extrapolating positively from these findings alone.

3. GENERAL DISCUSSION

Both experiments attempted to duplicate the findings of learning benefits attributed to the addition of non-task related variability seen in "differential learning" (Schollhorn, *et al.,* 2006). This technique had shown to benefit learning across various skill types and levels in applied settings (Wagner & Muller, 2008; Schollhorn *et al.*, 2006; Beckmann & Schöllhorn, 2003). However, when we brought similar ideas that shared common mechanisms with differential learning into the laboratory, we no longer found an advantage for added non-task related variability, for either experiment. Although we found that the groups with added variability were still able to acquire the 90^{o} RP pattern, in contrast to expectations, neither group improved more than those who practiced without added variability.

3.1 Task Properties

One possible explanation for our failure to find group differences is the type of task we used. We thought the framework of coordination dynamics would be a great arena to showcase the benefits of added variability. In dynamics, variability is thought to be important for change. We had a novel and relatively difficult task to teach, but one where acquisition is possible over a short time and a task where variability is thought to be an important aspect. One possible explanation why this task did not work is that it is a closed skill, (i.e., has a finite solution) with limited degrees of freedom to the movement as the action had to take place on a fixed manipulanda where rotation was only possible about the elbow joint. The positive results of previous (non-task related variability) research were with more open skills, for example, soccer, shot put, tennis, volleyball, and handball. Open skills provide better opportunity for the learner to develop an optimal solution on their own in order to organize and execute all the degrees of freedom they have to work with.

If the task is designed such that an outcome can be reached through multiple solutions, than it is more likely that variability will help in finding the optimal solution through exploration of the task dynamics. It is possible that the usefulness of added random variability was limited because the learner had a confined workspace in which the variability could work. For example, we saw that in certain conditions the variability provided a small, non-significant, advantage. Perhaps the small size of this difference was due to a limitation of the amount of freedom, or openness, within the task. Causing extra exploration of the environment was not useful for this task because it was constrained in terms of both the solution (what had to be done to achieve the goal) and the environment (the arms being on the manipulanda). On the other hand, another form of variability, contextual interference (Maslovat *et al.*, 2004; Tsutsui *et al.*, 1998), has been shown to aid acquisition of this task.

There are some positive and negative effects from task-related variability with this task. Although the results from Tsutsui *et al.* (1998) showed benefits for random in comparison to blocked practice, these results were limited to the more extreme comparison of a blocked versus a random group, where skills changed across days, rather than within a day for the former groups. This may indicate that this type of task is not as robust at showing benefits from added variability, or perhaps that only a small amount of variability may be appropriate for this task. Furthermore, variability of practice literature has generally shown an improvement for only the absolute features of a movement and not the relative features. Our task was to learn a new relative timing between the limbs, and we showed no benefit to added variability. Other researchers (Shea *et al.*, 2001) have shown negative effects when trying to learn relative durations with a variable-random practice schedule. Because others have shown these negative effects for task-related variability, perhaps our null effect could be the result of some benefits from added non-task related variability (such as experience of task dynamics) being countered by negative effects from variability when learning a relative timing task.

Consequently, although some of the results can potentially be explained by the nature of the task, it is unlikely the task is wholly the cause. Future research in the area of non-task related variability should consider the type of task, especially in terms of the amount of degrees of freedom the task has to vary; that said, research in this area should not limit itself to tasks with high degrees of freedom, as the usefulness of other forms of variability have not being limited by such constraints.

3.2 Externally vs. Internally-Generated Variability

With this type of bimanual coordination task, we were able to provide highly controlled conditions, unlike any prior research in this area. Therefore, confounding variables outside the experiment were greatly reduced. Previous research using non-task related variability often used an intervention strategy (e.g. Schollhorn *et al.*, 2006) that took place over a long period of time. This can bring in possible confounding variables, for example, outside sources of consistent practice, transfer of learning from other means, observational learning, and consolidation. By using a task and procedures that allowed for learning over a short period of time, we were able to limit most concerns related to outside influences. Additionally, the perturbations themselves were controlled via a computer in terms of type, size, amount, and duration. By comparison, past research has created variability through delivering verbal instructions for various body actions during movement execution, as well as varying external parameters (e.g. Schollhorn *et al.*, 2006). We were also able to more accurately measure error and performance than previous research in this area (e.g. Schollhorn *et al.*, 2006; who used assigned values to different areas of a soccer net). Our methods assured that the variability was consistent across participants.

However, our failure to show benefits from this variability brings up the possibility that the learner needs more control over their own variability in order to learn. If the learner is instructed to create variability they will generate a variety of motor commands; in contrast to our experiments, where they only needed to generate motor commands in response to the added variability. We pilot tested two additional participants in conditions similar to Experiment 1, with the Lissajous feedback, except they were instructed to bring variability into their own practice, instead of having the computer-generated variability. There was no indication that these participants gained anything from this manipulation. Furthermore, the addition of non-task related variability is expected to be beneficial due to forcing the learner to adapt to continuously changing situations and the resulting exploration of the task dynamics. In which case, it should not matter if the movement is self-generated.

There are differences in performing self-generated movement variations, in comparison to performing the movement with externally-produced variations; self-generated movement variations would involve the planning of an action to be variable (that is the small variations that one would be required to achieve would require small variations in the planning of the action) and would therefore require one to self-generate the various motor commands necessary. Evidence of the advantage of self-generated error versus externally produced error has also been shown using error-augmentation techniques (Domingo & Ferris, 2010). Using a beam-walking task, externally-induced errors failed to aid balance control; however, there was a positive relationship between self-induced error in torso variability and accuracy in beam walking.

Alternatively, performing the movement with externally-produced variations requires an active response and updating of current motor commands; the motor commands generated in this situation could be to correct the errors generated by the external force, rather than planning an action. For example, in some instances, it is possible a motor command could be used to overcome and adjust to the perturbation, but not be a solution or a motor program that works to recreate the original task goal (i.e., the intended relative phase pattern). This creates a potential difference in the processing involved in planning an action compared to processing involved in the response and updating of a motor command. Further investigation into the influence of planning an action and responding to a perturbation with variability, specifically non-task related variability, is necessary. Moreover, if the nature of the variability, whether it is self-generated or induced, is an important consideration, than the belief that it is simply an increased exploration of the task dynamics that potentially facilitates skill acquisition (e.g. Shollhorn, *et al.*, 2006) needs to be questioned.

3.3 When to Add Variability and How Much?

The combination of different factors on cognitive processing has been explained with the "Challenge Point" framework (Guadagnoli & Lee, 2004), which proposes that the effectiveness of added variability in practice is mediated by the cognitive processing demands of the task. In part, because of the cognitive demands of the task, in Experiment 1 we administered the variability only later in practice – after the cognitive demands of the task were lower, because the participants had improved. Another reason for the late introduction of variability was due to a proposed need to stabilize the movement before variability can be helpful (Shea & Wulf, 2005). However, we did not see any benefit to this late introduction of variability or to the early introduction of variability as with Experiment 2.

Feedback is also an important consideration in determining cognitive demand, and, as we saw in Experiment 2, participants performed with much higher variability (criterion trials in practice, M_{SD} = 38.40°, SD = 21.08°) when they did not receive Lissajous feedback in comparison to when they did receive Lissajous feedback in Experiment 1 (criterion trials, M_{SD} = 12.30°, SD = 2.78°). This resulted in higher variability for the control group in Experiment 2 in comparison to Experiment 1, and, although, the perturbations created more variability in comparison to control variability in both experiments, group differences were not statistically different in Experiment 2.

It could even be argued that the levels of variability were too high even in Experiment 1, for variability to be potentially useful later in practice. Participants had only received half a day of practice and, hence, the movement at this stage might still be considered relatively unstable. So, in summary, for this type of coordination task, perhaps the need for added variability never arises because performance remains relatively variable. Future research may want to investigate a simpler task, or a task that can be performed more consistently once acquired, or one where more practice experience has been attained.

We also attempted introducing variability throughout practice, partially because there is evidence that variability early on would help break away from natural attractors (Hodges & Franks, 2002; Frank *et al.*, 2008). However, we saw no benefit to the rate of acquisition with variability added early. It is possible that in some of the previous research (Hodges & Franks, 2002) that showed a benefit of early variability, it was not the variability that caused the improved performance. Rather, the withholding of instructions resulted in both improved performance and increased variability early in practice. However, there remains strong evidence that variability precedes a change in relative phase (Haken, Kelso, & Bunz, 1985); indeed, Schollhorn and colleagues (e.g. Franks *et al.*, 2008) have argued that learning via differential methods is preceded by a variability-induced bifurcation. In order to further investigate the potential benefit of introducing variability early, we pilot tested two additional groups (n = 4), receiving perturbations either exclusively early or late in practice. Procedures were similar to Experiment 2 (i.e., pendula stimulus). However, these data again showed no group differences. As suggested above, perhaps variability needs to be self-generated in order to assist early learning of a new relative phase. When participants are not given instructions they inherently generate more variability in their movement, whereas mechanically forcing the participants to increase variability appears to perhaps be too direct of an approach. When mechanically perturbed, participants may focus cognitive processing on recovering from the perturbation, which may involve different memory resources than are used to recall the intended movement in retention testing.

Another difference between our design, and those of Schollhorn and colleagues, is that the induced variability for our study was a consistent force opposing the movement and it remained active for a consistent time (1 second). Although, we did randomly distribute the perturbations within each practice trial, future research may want to vary the amount, size and duration of the force (variability) manipulation. We administered perturbations on 80% of trials (either in the second half or throughout practice) and it was a fairly difficult force to overcome. Given our results, it is likely that for a skill as difficult as the one we used, it would be better to reduce both the frequency and strength of the variability. Our goal was to give the participants the most experience of the increased range of dynamic workspace, with only occasional criterion trials so we could compare performance to the control group. However, it appears other mechanisms may need to be considered, such as the 'Challenge Point', when trying to implement an optimal level of variability in this task.

3.4 Other Possible Considerations and Limitations

We believe the inclusion of added variability can positively benefit motivation and cognitive engagement in the task. We did not see any benefit from the type of variability we administered. However, one reason that variability (e.g. lift hands above head) used in differential learning has worked for sport skills (usually with experienced athletes) is that it keeps participants more engaged and motivated. Therefore, it is quite possible that the mechanism underlying positive effects of this type of variability are more motivational in nature, linked to greater positive engagement in practice, rather than the purported mechanism for differential learning, forcing the learner to adapt and react in continuously changing situations, which creates variability that promotes self-organization and discovery of optimal motor solutions in a wider dynamical workspace.

Error augmentation shares some commonalities with differential learning, both serve to create more errors in practice; however, error augmentation enhances errors in direct relation to the task goal (e.g., overshoot or undershoot), whereas, differential learning techniques create more errors in practice in a manner which is non-related to the task goals and are simply an exploration of the possible task solutions. Our manipulation created more errors as well as being a greater exploration of the task dynamics. The experience of additional errors in practice gives the performer added feedback about performance and encourages the detection and correction of errors. Therefore, participants should be better prepared to deal with errors in retention or later performance, due to enhanced detecting and correcting abilities. Patton & Mussa-Ivaldi (2004) used opposing forces to cause high errors during practice and when the forces were removed the subjects reached correctly. However, the higher errors we created with opposing forces did not improve performance in retention for our task. Perhaps the participants need errors to have structure, (i.e., be proportionally related to the task goal), and they are not able to improve from errors which are random in nature. Furthermore, we expected to see a faster rate of acquisition for the Perturbation group in Experiment 2, due to the increased errors early in practice, but we did not. Evidence from Emken & Reinkensmeyer (2005) showed that early error enhancement benefited subsequent trials. Perhaps the reason we did not find improvement is that Emken & Reinkensmeyer (2005) reduced the magnitude of the force after the first trial. Future research may want to attempt gradually decreasing the size or amount of perturbations.

3.5 Conclusion

In conclusion, in two experiments, we failed to find evidence that externally-added, non-task related variability, provided a beneficial effect for skill acquisition. Therefore, some caution is recommended in using this type of technique to enhance the skill acquisition process. Although there are some potentially promising results from the differential learning literature and the error-augmentation literature, the evidence is somewhat sparse and mostly limited to one group of researchers, at least in the former case (Schollhorn *et al.*, 2006). Moreover, in terms of error-augmentation, the variability is performance dependent whereby errors are 'augmented' or increased, rather than added in a random fashion, independent of current performance (as was the case with our methods). Finding the optimal amount of variability to include in practice is likely mediated by more than just exploring a dynamic workspace, and should include factors such as motivation, task difficulty, and skill level of the participant.

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