AN INVESTIGATION OF THE SPECIFICITY OF MOTOR LEARNING HYPOTHESIS

by

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B.Sc. (Kinesiology), Simon Fraser University, 1993

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An Investigation of the Specificity of Motor Learning Hypothesis

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ABSTRACT

Motor learning specificity has a long history, beginning with F. M. Henry (e.g. Henry, 1968). Recent work has focused on the specificity of learning with regards to the sensory information available when learning and performing a movement. These learning studies typically employed manual aiming movements. This thesis attempted to replicate and extend previous work. Predictions were made pitting the specificity of motor learning hypothesis against Schema theory. In experiment 1, 3 groups of 10 subjects practised the movement (a series of flexions and extensions at the elbow, defined spatially and temporally): one practised the movement for 300 trials with visually presented on-line kinematic feedback while the other two did not, one of which did 300 trials (HP), the other 50 (LP). Pretest and posttest sessions of 10 trials each were performed. Measures were obtained that characterized overall, spatial, and temporal performance. Results indicated that all groups improved with practise. In the posttest, the LP group maintained performance levels, while providing the HP group with the feedback resulted in transient performance decrements, indicating an inability to use the novel visual information.

In experiment 2 subjects practised the same movement as in experiment 1 with the on-line feedback and a movement duration of 2.20 sec. Half of the 42 subjects performed 50 practise trials (LP), the other half 300 (HP). The subjects within the two levels of practice were divided by movement duration in the pretest (10 trials) and posttest (20 trials), performing either a 2.20, a 2.64, or a 3.30 sec. movement. All groups improved over practise, with more practise yielding superior performance. The LP groups demonstrated the ability to generalize to the unpractised durations, while performance at the novel durations caused performance decrements for the HP groups. In addition to the HP groups' inability to generalize, performance at the novel durations appeared to decrease as the practice and posttest durations diverged.
These results suggest that motor learning is the process of forming a sensorimotor representation within the C.N.S. that is specific to the conditions experienced in practice. The more practice, the more refined and thus specific the sensorimotor representation becomes. Also, there was evidence from experiment 2 to suggest that the ability to generalize displays a gradient, similar to stimulus generalization. These results were discussed in terms of their implications with regards to motor learning paradigms, training and simulation, and models of motor learning.
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INTRODUCTION

Motor Learning

The repertoire of human movements is almost infinite. People can tie their shoes, throw a curveball, operate a forklift, and perform a myriad of other tasks involving coordinated movement of the limbs and/or trunk. Investigations into how humans learn to coordinate their movements and under what conditions learning is optimized are numerous. This thesis investigates how humans learn a movement requiring spatial and temporal coordination with the intent of answering three questions. First, how does changing certain parameters of the movement or sensory feedback about the movement affect performance? Second, how does the effect of these changes vary with the amount of practise? Finally, what do the results suggest about the way learning occurs in the central nervous system?

General introduction to the importance of the topic

There are a number of benefits that result from the study of motor learning. Observing subjects as they practise and learn a movement provides information about the processes involved that may lead to inferences about what is occurring at the neural level. Inferences about the neural processes that underlie motor learning and the eventual neural representation of the movement are possible, and contribute to the academic knowledge about learning. In addition to the theoretical importance of such research, there are practical benefits to studying motor learning. By observing how learning occurs under different conditions the formation of successful training protocols and optimal training environments is possible in sport, industrial, and therapeutic settings.

There are difficulties in studying learning, however. As alluded to above, researchers must infer what occurs in the central nervous system as subjects practise and learn a movement. Thus, the study of motor learning is inherently difficult because one cannot observe learning directly (Magill, 1989; Schmidt, 1988). Without the ability to peer
into the central nervous system and see the changes that occur as a result of learning, we are forced to infer learning from observations of performance. Therefore, behavioural consequences of learning, like increases in movement accuracy and consistency are indicators of improved performance from which learning can be inferred.

Because of the necessity of inferring learning, some researchers have suggested that learning can only be evaluated by the use of test, or transfer, trials (e.g. Bransford et al., 1979). This philosophy will not be applied to the present thesis for two reasons. First, for the purpose of this thesis it is assumed that human motor learning occurs as modeled by connectionist systems (e.g. Churchland, 1989; Rumelhart, 1989). Within this framework, each attempt at a movement will result in changes to the strengths of the connections of a network of neurons in the central nervous system. Coactivation of connected neurons is seen as resulting in the strengthening of the connections between those neurons. Similarly, connected neurons which are not activated together have the strengths of their connections decreased. Through this process the network makes iterational modifications to the strengths of the connections, resulting in a network that has 'learned' to perform the movement. Therefore, under conditions where variables like fatigue, boredom, and motivations are controlled, it is inevitable that practise leads to learning, and transfer tests (e.g. Magill, 1989; Schmidt, 1988) are unnecessary to evaluate learning. Second, the purpose of this thesis is to investigate the extent to which learning is specific to practice conditions. Therefore, to evaluate learning based on performance of a movement that is a variation of what was actually practised seems ill advised.

Another difficulty with the laboratory study of motor learning is the need to create novel learning situations. This is necessary to limit the influence of the subjects' past experiences on the learning of the experimental task. As well, movements must be chosen that allow subjects to learn quickly enough to attain a reasonable level of movement proficiency. In addition, movements used in experiments must also allow easy
measurement and quantification of performance, so that improvement with practise can be demonstrated. Another short-coming of laboratory experiments is that it is very difficult to provide subjects with the opportunity to have sufficient practise to achieve truly skilled performance. Therefore, inferences about the learning processes are often made only on the basis of what is observed of the initial portion of the learning process.

**Specificity-Based Definition of Learning**

**Specificity Stated Simply**

The present thesis investigates the specificity of motor learning hypothesis. A more detailed definition of learning will be formulated in a subsequent section of this introduction, but for now the hypothesis can be very simply stated: the more one practises a movement, the better one gets at that movement under those conditions. With this simplistic definition of the specificity of motor learning hypothesis now stated it seems appropriate to review the literature that led to the more formal formulation of this hypothesis as presented in this thesis.

**Historical Development of the Hypothesis**

The formal, specificity based definition of learning can be traced back across almost 40 years of literature. That literature is reviewed here in chronological order, to demonstrate the evolution of the hypothesis.

The notion that motor skills were specific can be seen as originating from the work of Franklin Henry. Henry (1968) argued that practising a movement improves performance of that movement, but that this improvement in performance cannot be reliably used to predict the improvement in another related movement. This is because the transfer from a practised movement to another is very specific (Henry, 1968). This notion of specificity was formulated within the framework of individual difference theories.

In the tradition of Henry, Bachman (1961) investigated the degree of specificity in learning two different motor skills requiring balance. Subjects practised both a stabilometer
task and a free-standing ladder climbing task. Both tasks require large muscle groups to act in a coordinated manner to maintain balance, and one could predict that improved performance on one balance task would correlate with similar improvements on the second balance task. However, in keeping with Henry's (1968) hypothesis, correlations between performance on the stabilometer task and the ladder climbing task were near zero, and often negative. Bachman (1961) indicated that such results rule out the notion of a general motor coordination ability for balance and of the presence of a general motor learning ability. These results do support the idea that motor abilities are task specific for performance and for learning (Bachman, 1961).

Adams, Goetz, and Marshall (1972) performed an experiment designed to investigate the use of feedback in motor learning. The goal of this investigation was not to test the specificity hypothesis, but to test the hypothesis that with learning subjects progress from closed-loop to open-loop control of movements. The results nonetheless suggest specificity of motor learning. Adams et al. (1972) had subjects learn a linear positioning task, in which the criterion movement was 10 inches in extent. Subjects had either a low degree of practise (15 trials) or a high degree of practise (150 trials) with knowledge of results (KR) regarding direction and amplitude of error. The positioning task was practised under either minimal feedback (no visual information, masking white noise, and no spring tension on a near-frictionless slide) or augmented feedback (full vision, auditory feedback, and a spring attached to the slide to increase proprioceptive information). In test trials without KR administered after the completion of the practice trials, subjects transferred to the other feedback condition or retained the original condition. A detailed look at two groups in particular, those that transferred from minimal to augmented feedback for both levels of practise, yields evidence for the specificity hypothesis. Transferring from minimal to augmented feedback caused decrements in performance for both groups. However, the more highly practised group had a greater relative decrement in transfer
performance, with absolute error increasing by 0.93 inches for the high practise group while the increase was 0.54 inches for the low practise group.

In a more recent study Proteau et al. (1987) investigated the hypothesis that the contribution of sensory information to the control of movement becomes less pronounced the more extensively a movement is practised (e.g. Fitts & Posner, 1967). Subjects were trained to point to a target light using a stylus. The amount of practise was manipulated (200 vs. 2000 trials) and the amount of visual information was varied (full vision vs. vision of target only), yielding four different experimental conditions. After the acquisition trials, all groups transferred to the target only condition. Two lines of evidence suggested that performance of a motor task is specific to the sensory conditions that prevail during learning. First, the group that practised for 200 trials in the target only condition showed a 67% increase in spatial error in the transfer trials without KR relative to acquisition while the target only group that had 2000 trials showed no increase in spatial error. The second, and more compelling, line of evidence comes from the transfer results of the full vision groups. A 400% increase in spatial error during transfer was suffered by the group that had 2000 practise trials in the full vision condition, while the increase was only 100% for the group that practised 200 trials with full vision. These results indicate that the representation of the movement that is formed during learning is optimally configured to lead to successful completion of the movement and is more affected by the change in the sensory information after extensive practise. These results, therefore, are evidence against claims that learning occurs in a closed-loop to open-loop fashion. This led Proteau et al. (1987) to suggest that motor learning is the formation of an internal sensorimotor representation of the movement that is specific to the conditions that are encountered during acquisition.

Using a variation of the pointing task, Elliott and Jaeger (1988) tested subjects in three visual conditions: lights on, lights off, and lights off with a 2 second delay. Prism
spectacles were worn by the subjects to make the target appear closer, and thus induce pointing error. Subjects practised the right-handed pointing task in one of the three visual conditions for 70 trials, then performed 10 trials of each condition, followed by ten trials of each condition pointing with the left hand. Subjects did not have vision of the target during the execution of the movement. Elliott and Jaeger (1988) indicated that their results provided evidence supporting both generalizability and specificity of learning. The authors indicated that their results suggest that learning (in this case) closed skills involves learning to use the sensory information (i.e. vision) that is available. Subjects that practised with the absence of visual information suffered performance disruptions when the vision conditions changed. Elliott and Jaeger (1988) agreed with Proteau et al. (1987) that these types of results are damaging to models of learning that predict a shift from closed to open loop control with practise.

Proteau and Cournoyer (1990) investigated the effect of varying levels of visual feedback during a manual aiming task. Subjects practised in one of the three different visual conditions (vision of target, arm, and stylus; vision of stylus and target; vision of target) for either 15 or 150 trials. After the practice trials, all subjects performed 15 transfer trials in the vision of target only condition. Results indicated that endpoint accuracy was decreased during transfer trials for all six groups. An interaction between experimental phase (practise versus transfer) and feedback condition was found for spatial accuracy in the y axis for the groups performing 150 trials. Transfer had a graded effect on the different visual feedback groups. The vision of target only group suffered virtually no decrement, the vision of arm, stylus, and target group suffered a large decrement, while the vision of stylus and target group suffered an intermediate performance decrement. A similar but non-significant trend (p=.08) was found for spatial accuracy in the x axis. This trend was not apparent in the groups that performed 15 trials. Under these circumstances, all groups suffered an increase in root mean square error in transfer. The authors
suggested that their results contributed to the support for the specificity of motor learning hypothesis. Proteau and Cournoyer (1990) suggest that their findings are the result of a shift from intramodal to intermodal comparisons. That is, comparisons of afferent information to some internal representation of the movement, changing to comparisons of afferent information to an integrated internal representation of the movement. They concluded that the underlying principle for movement learning is the integration of different types of sensory feedback that are used in concert with central planning processes to form the basis of the movement representation. However, this was tempered by the admission of the authors that the results are not strongly compelling, due perhaps to the low number of subjects (5 per group) or the relatively low number of practise trials for the moderately practised group.

One possible criticism of this study is that removing vision of the limb (and, thus, the ability to perform vision-aided corrective movements as the pointing movement unfolds) should obviously result in a decrease in spatial aiming accuracy. Proteau, Marteniuk, and Lévesque (1992) attempted to replicate and extend the results of Proteau et al. (1987) by investigating what happened when subjects were given additional movement-relevant information in transfer. Proteau et al. (1992) hypothesized that motor learning was specific to the sensory feedback information available during acquisition. Specifically, adding a relevant source of movement control information (vision of the limb) to a task that was previously practised without this information would result in performance decrement, relative to a control condition. A target pointing task was used which was very similar to that used by Proteau et al. (1987). Two groups were trained in either the vision of target only or the full vision conditions. Both groups performed in a pretest, under the full vision condition, for 40 trials. The two groups then performed 200 acquisition trials in their assigned visual condition, receiving KR regarding spatial accuracy (X and Y) and movement time (if required). Forty transfer trials were then performed, and all subjects
performed in the full vision condition, with no spatial or temporal KR. Both groups then performed a second set of acquisition trials for a further 1000 trials with KR, followed by a second set of transfer trials without KR.

Proteau et al. (1992) identified two aspects of the results that they claim support the specificity of learning hypothesis. First, after 1200 practise trials in the vision of target only condition, introducing vision of the limb in transfer caused a significant increase in spatial error, and no such increase in error was seen in transfer after 200 trials of acquisition. Second, relative to the pretest results, the transfer performances of the vision of target only group both show increased spatial error. This is an example of true negative transfer, as practising one movement caused performance in another movement to become worse than initial performance (pretest). This, Proteau et al. (1992) posited, is because introducing vision after learning to perform the movement without it interferes with what had been previously learned. Proteau et al. (1992) made the point that these results, as with a number of the previously mentioned studies, directly contradicted any proposition suggesting that learning involves progressing from a closed-loop to an open-loop mode of control.

In a chapter that reviews some of this literature, Marteniuk (1992) suggests that the results of these studies support the idea that learning results in some change within the central nervous system that results in the efficient planning, execution, and movement correction processes necessary for skilled movement. These changes are specific to the task and types of information received by the learner during practise. Proteau (1992) also provided a review of this literature. He suggested that "learning results in a representation consisting of an integration of all relevant information about the movement task...which becomes more tightly integrated with experience at the task" (p. 96). The formalized definition of learning presented here is based on these chapters.
The more recent research investigating specificity of motor learning (i.e. Elliott & Jaeger, 1988; Proteau & Cournoyer, 1990; Proteau et al., 1987; Proteau et al., 1992) is not without its shortcomings. These studies all used pointing movements as the movement that subjects were to learn. This movement is probably not one that requires a lot of practice to refine as humans are able to point accurately at a very early age (Hay, 1978). In some studies, however, mechanical perturbations were applied during the movement, requiring subjects to learn to overcome this perturbation while pointing (e.g. Proteau et al., 1992), which increases the complexity and difficulty of the movement. When compared to a more real world, or ecologically valid, movements like a tennis serve, it becomes obvious that simple pointing is too simple a task to use to study learning in a meaningful way. As a measure of their simplicity these pointing movements require no joint reversals and were of very short durations (ranging from 300 to 600 msec across experiments).

In addition, while some of this research has used a large number of practice trials (Proteau et al., 1987 - 2000 trials; Proteau et al., 1992 - 1200 trials), other studies have used very few practice trials: 70 trials (Elliott & Jaeger, 1988) and 150 trials (Proteau & Cournoyer, 1990). This low number of practice trials may suffice to attain high levels of performance in these simple pointing tasks but are not appropriate for wanting to generalize to learning other, more complex, movements.

The present experiments were designed with these shortcomings in mind, and were intended to test the specificity of motor learning hypothesis more rigorously and yield more generalizable results.

**Formal Definition**

A number of researchers have presented variations on the conceptualization of movements being stored in the central nervous system as sensorimotor representations. Abbs, Gracco, and Cole (1984), for example, described motor programs as "...the representation of the dynamic processes whereby the appropriate sensorimotor
contingencies are set up to ensure cooperative complementary contributions of the multiple actions to a common, predetermined goal” (pp. 214-215, italics theirs). Motor learning, then, is the development of such programs, which are able to construct the appropriate sensorimotor contingencies for the successful performance of the required movements.

Marteniuk (1992) put forth a similar conceptualization of motor learning based on studies performed by Proteau and colleagues (Proteau & Cournoyer, 1990; Proteau et al., 1987; Proteau et al., 1992). The results of these and other learning studies have suggested that learning a movement results in the formation of a sensorimotor representation of the movement that is specific to the sensory conditions experienced during the learning process (Marteniuk, 1992; Proteau et al., 1987). This conclusion was reached based on the detrimental effects on performance observed when highly practised subjects were made to perform under conditions of novel sensory information.

While drawing on previous formulations of the specificity of learning hypothesis, a more explicit specificity-based definition of learning is proposed here:

Closed movement motor learning is the construction of a sensorimotor representation of the movement within the C.N.S. over practice trials that is based on, and specific to, the conditions that exist during practice.

Closed movements are defined similarly to closed skills: That is, movements that are performed in a movement environment that is stable and predictable (Magill, 1989). This differentiation between "skills" and "movements" is important, as one can learn a movement without necessarily becoming skilled at that movement. Newell (1985) defines skill as the assigning of optimal values to the parameters required for the control and coordination of movement. One can learn a movement, perform it in a coordinated manner, and control the moving segments without ever achieving optimal values for the performance variables.
This internal sensorimotor representation is developed over learning to optimally represent and process information relevant to the successful performance of the learned movement (Marteniuk, 1992).

**What is stored in this sensorimotor representation?**

There are a number of sources of information that are stored in this hypothesized sensorimotor representation. Obviously, these can divided into two main forms of information, sensory and motor, each of which can be further decomposed.

**Sensory information.** Sherrington (1947) described three classes of sensory receptors, each providing different information. Interoceptive information arises primarily from the gastrointestinal tract, and is assumed to be of little importance in the planning and control of movements. In contrast, the other two receptor classes are important to movement production. Exteroceptors provide information from the body's interface with the external environment. Specific receptors exist in this exteroceptive field adapted to pressure, temperature, light, sound, and pain (Sherrington, 1947). The third class of receptors, proprioceptors, provide information regarding the movement and orientation of one's own body. These latter two classes of sensory receptors can be further subdivided according to the type of receptor and therefore the type of information provided.

The dominant exteroceptive sense for controlling movements is vision (Schmidt, 1988). This sense provides information about the environment with which the individual is interacting, and aids in the definition of the movement requirements and constraints. Auditory information may have a minor or even negligible contribution to most movements, but can be of great importance in tasks like playing musical instruments.

There are many different classes of proprioceptors, each providing specific information regarding the state of the movement system (the body and limbs). Muscle spindles, arranged in parallel with muscle fibers, provide information regarding length, change of length, and rate of change of length of muscle (Gordon & Ghez, 1991). Golgi
tendon organs are in series with muscle fibers and provide information about changes in muscle tension (Gordon & Ghez, 1991). Cutaneous receptors sense pressure and deformation of the skin, which is especially important when one is interacting with objects in the movement environment. Joint receptors provide information regarding movement and the position of the joint (capsule) (Johansson, Sjölander, & Sojka, 1991), and may be most informative at extremes of the joint's range of motion (Schmidt, 1985). Muscular free nerve endings also contribute afferent information about movement, and appear to be most sensitive to high levels of muscle stretch and force (Cleland, Hayward, & Rymer, 1990).

Which of the above sources of information, both exteroceptive and proprioceptive, are stored in the sensorimotor representation of movement? All, to varying degrees, are capable of contributing relevant afferent information prior to, during, and as a consequence of a movement. According to the specificity hypothesis, only those which are useful in guiding the movement will be present in the sensorimotor representation. Without some sort of pathological condition or experimental intervention, proprioceptive information will be present. Auditory information may not be relevant to the task, and would therefore not be present in the same way on each movement attempt. Consequently, the auditory information will not be strongly represented in the sensorimotor representation. Visual information would similarly appear in the sensorimotor representation of the movement if it was utilized during acquisition (but see e.g. Kunzendorf & Wigner, 1985, for an example of apparently irrelevant sensory information affecting performance).

In addition to the intrinsic sensory information, there are also extrinsic forms of sensory information. Primarily these are knowledge of results and knowledge of performance. Knowledge of results (KR) is information about the outcome of the movement in terms of its goal (Schmidt, 1985). This can often be redundant with intrinsic information (e.g. one sees that they missed the free throw [intrinsic information], and a
coach tells them they missed [KR]). Knowledge of performance (KP) is feedback regarding the movement pattern that is produced, regardless of the movement outcome (e.g. one can have good form and still miss a free throw) (Schmidt, 1988). Both types of information are useful when acquiring a movement, but they are probably more useful in error correction on an attempt to attempt basis, rather than as an integral part of the movement representation.

**Motor information:** As with sensory information, there are many candidates for the motor information represented centrally. However, unlike sensory information for which it is conceivable that any or all sources of information can contribute to the central representation, little is known about what muscle variables are represented centrally. In discussions of limb movements, Stein (1982) identified five muscle variables that could potentially be controlled by the nervous system. These muscle variables are force, length, velocity, stiffness, and viscosity. After consideration of these five variables, Stein concluded by suggesting that there is not one single control variable, and that the variable controlled is dependent upon the type of limb movement. Whatever the control variable(s) is (are), it (they) must somehow characterize the movement in the central sensorimotor representation.

In addition to the muscle control variables, there must also be some encoding of the timing or sequencing of the submovements that make up a movement, as coordinated movements require temporal as well as spatial coordination.

How this muscle information is represented centrally is unknown. Theories range from central prescriptions of movement (Keele, 1968) to Bernstein's (1967) conviction that the "motor effect of the central impulse cannot be decided at the center but is decided entirely at the periphery" (p. 106, italics his). It is not the purpose of this thesis to determine what form the motor information takes in the sensorimotor representation, nor is it to uncover if the information is detailed or general. This thesis investigates the existence
of an hypothesized sensorimotor representation of movements, and to determine if, as has been proposed (e.g. Proteau et al., 1987), this representation is highly specific to the conditions that exist during acquisition of the movement.

**Why only closed movements?**

The definition of learning given above is delimited to the learning of closed movements (defined above). There are a number of reasons why this definition of motor learning may apply only to closed movements. First, this definition of learning was formulated based on the results and interpretations of experiments using laboratory tasks (e.g. target pointing studies) in which the movement environment was unchanging for the duration of each trial. Second, from a methodological standpoint, the ability to perform a closed movement is more readily quantifiable. Third, since by definition closed movements occur in unchanging, predictable environments, they afford the rigorous regulatory control necessary for experiments. Finally, and importantly, the specificity of learning hypothesis may not be compatible with open movement learning. When learning an open movement, the motor demands and sensory aspects of the movement and the movement environment change from attempt to attempt. Thus, the sensorimotor representation that is formed will not be sharply defined. This form of sensorimotor representation may allow the learner to perform under various conditions, including novel conditions, and allow the learner to generalize from the learned movement to a new, related movement. This notion is consistent with a connectionist viewpoint. Thus, when learning open movements, a highly specific sensorimotor representation would not be formed, and the specificity in performance that is the signature effect of the specificity hypothesis would not occur.
Alternative Theoretical Approaches to the Specificity Hypothesis and their Predictions

The two experiments presented in this thesis can be used to test the predictions of other theories of motor learning. The first experiment tests the prediction made by a number of theories that as one learns a movement, the control of that movement changes from closed-loop (feedback dependent) to open-loop (feedback independent) control. The second experiment investigates the prediction that a movement can be scaled in time once it is well learned without affecting the quality of the movement. A number of theories that produce one or both of these predictions or that make general predictions about the affects of transfer are outlined below.

The diminishing influence of sensory information

Fitts and Posner (1967) described three phases in skill learning. One characteristic of progressing through these stages of learning is a decrease in the attention required to sensory information. In the early, or cognitive, phase Fitts and Posner state that it is usually necessary for the learner to attend to cues, events, and responses that will later not be attended to. This is reiterated in their description of the final, or autonomous, phase as highly practised skills are likened to reflexes, which are less directly subject to cognitive control. In addition, these authors state that highly practised skills are less subject to interference from distractive movements or information.

Schmidt (1975) proposed that the main problem when learning a movement is to proceed away from the initial feedback controlled movements that result in jerky performances toward fluidly executed movements which are controlled centrally. This progression from reliance upon sensory feedback and the ability to prescribe movements was investigated by Schmidt and McCabe (1976). Using an index of preprogramming to characterize the mode of movement planning and control, it was determined that the control
of timing movements changed from closed-loop to open-loop control as practice progressed.

These two theories, Fitts and Posner's stages of motor learning and Schmidt's Schema/generalized motor program theory, would predict decreasing performance decrements when the sensory feedback of a movement is changed at increasing levels of practice. This proposition is in direct opposition to the specificity of motor learning hypothesis. The results of experiment 1 will support one or the other of these conflicting predictions.

Scaling a movement in time

Schmidt's (1975) Schema/generalized motor program theory of motor learning assumes that the generalized motor program represents the commands for a class of related movements. According to this theory, schemata, or rules, are abstracted based on information resulting from the performance of a number of trials of a movement, as well as the initial movement conditions (Schmidt, 1975). One of these schemata is called the recall schema, and it specifies the response specifications for the generalized motor program, which is at the heart of the Schema idea (Schmidt, 1988). Which of the variants of the movement is actually performed is a function of the response specifications, or parameters, which are used prior to the movement's initiation to enable the execution of the program at a defined speed, with a defined force, etc. (Schmidt, 1975). One of these parameters is an overall duration parameter (Schmidt, 1988). This parameter allows one generalized motor program to specify the movement regardless of the speed at which it is performed. The movement as a whole is sped up or slowed down by this parameter; that is, the phasing or timing of the components of the movement are invariant, regardless of the overall duration (Schmidt, 1988).
Similarly, McKay’s (1982) associationist theory for learning and controlling skilled behaviours predicts that a movement can be performed with the correct timing of its component submovements regardless of the overall movement time.

Therefore, both Schmidt’s Schema/ generalized motor program theory and McKay’s theory predict that scaling a movement in time should not affect the performance of a previously learned movement. Again, this prediction is contrary to that of the specificity of motor learning hypothesis, and will be tested in experiment 2.

Theories of Transfer

The ability to transfer, or generalize what was learned to a new situation, is related to the similarity of the two situations (Lieberman, 1990). The more the two situations diverge, the less transfer there will be to the new variation. Two motor learning theories with slightly different views of what must be similar between the two tasks offer explanations of transfer performance effects.

The transfer-appropriate processing approach focuses on the relationship between the conditions of practice and test situations (Bransford, Franks, Morris, & Stein, 1979). This theory contends that transfer paradigms are often inappropriately used (Morris, Bransford, & Franks, 1977): If one group practises a task under condition A while another practises under condition B, if the transfer test is to perform under condition A the latter group is at a disadvantage, and will generally perform at a lower level of proficiency than the former group. Transfer from one task to another (or one version of a task to another version of that same task) is facilitated to the degree that the processing required to learn and perform one task is the same as for the second task (Lee, 1988).

This approach yields predictions similar to those of the specificity hypothesis: Groups that practise and are tested under the same conditions should show maintenance in their level of performance; groups that are well practised at one version of a task should suffer a decrease in performance when tested under different conditions. This theory’s
predictions deviate from those of the specificity of motor learning hypothesis when a group practises under one condition for a few trials (relative to the above mentioned well practised group), then is transferred to a different condition. Transfer-appropriate processing predicts decrements in transfer performance, while the specificity hypothesis predicts little or no performance decrements in transfer for such groups, or, in some instances, actual performance enhancements.

MacKay (1982) proposed an associationist theory to account for how skilled behaviours are represented in the central nervous system. According to this theory, hierarchically organized nodes comprise the motor program. There are two types of nodes, mental nodes which represent a class of actions and are cognitive units for controlling the movements, and the subordinate nodes of the muscle-movement system that represent patterns of muscle-specific activity. Nodal activation is serial in nature, such that each successive component of the behaviour is activated and thus performed in the correct sequence. While activation of a node is all or none, subthreshold activation of a node is called priming, and serves to prepare a node for activation. Priming occurs when a node that is activated raises the activation levels of related or connected nodes. These connections are formed through practise. Priming occurs in parallel, such that a node may be primed prior to its eventual sequential activation. A primed node's eventual activation occurs more rapidly, resulting in movement that are well practised being performed fluently and rapidly.

This theory states that the amount of positive transfer from one task to another is dependent on the amount of nodes that the two movements share. Negative transfer occurs when the shared nodes prime subordinate nodes that were useful for the initial movement but are extraneous to the completion of the transfer movement. This theory is similar to the specificity of motor learning hypothesis, having comparable mechanisms and yielding
similar predictions, except with regards to its predictions regarding scaling of movement time.

Motivations for these Experiments

The present thesis aims to expand on the specificity of motor learning literature by increasing the complexity of the movement to be learned. Moving away from the simple, rapid pointing movements provides a good test for the specificity hypothesis. This is the next logical step in the investigation of movement learning specificity.

The second experiment endeavours to extend the specificity results from those seen previously when the quality of sensory feedback was manipulated to the present manipulation of the duration of the movement. This experiment tests an implicit prediction of the hypothesis. Since the sensorimotor representations that are constructed with learning appear to be specific to the sensory conditions that are present during learning, the representation should also be specific to the motor aspects of the practised movement. In this instance, the specificity hypothesis is in direct opposition to Schema theory, which would predict that the motor program constructed during learning could be parameterized to accommodate the new movement duration.

In addition, these experiments, if support is found for the specificity of motor learning hypothesis, can be used as evidence against other theories of motor learning. In a related manner, support for the specificity hypothesis challenges the traditional use of transfer paradigms to evaluate the extent of learning for a comparative basis in motor learning experiments.

Brief Overview of the Experiments

The Movement and the Paradigm

In an attempt to overcome some of the short comings of the previous studies investigating the specificity of motor learning hypothesis (e.g. using simple pointing movements, and few practise trials. See previous section 'Historical Development of the
Hypothesis') a sequential flexion-extension movement about the elbow was used as the movement that subjects practised. This type of movement has been employed in previous learning studies and it has been demonstrated that subjects can learn complex movement patterns using this protocol (e.g. Bamford, 1985; Romanow, 1984). This movement requires both spatial and temporal accuracy in the attempted reproductions of a criterion movement, and therefore represents the characteristics of many of the movements humans learn (cf. Schmidt & Young, 1991).

The two experiments performed are based on the same general paradigm. Typically, control subjects practise the task under the same conditions that they are tested. Experimental subjects practise the movement under conditions unlike those they will encounter in the posttest trials. The experimental subjects are divided, half receiving a high number of practice trials and half receiving a low number of practice trials. Specific predictions are made for each experiment, and are stated generally below.

**Experiment 1**

Experiment 1 had as its goals the answering of two inter-related questions. First, it was an attempt to replicate the previous specificity results using a more complex movement. That is, is specificity in motor learning evident when subjects learn a serial angular positioning movement without beneficial feedback then transfer to conditions with this feedback, and is this performance change affected by practise in a graded manner? Second, does the influence of sensory information on the planning and control of a movement decrease with increased practise?

**Experiment 2**

The goals of Experiment 2 are extensions of those from Experiment 1. Again, a replication of the previous literature is sought, but in this case by changing the motor output and the consequent sensory feedback from practice to the test trials, instead of only the
feedback. This study attempted to extend the previous literature as well as the specificity of motor learning hypothesis itself by looking at the effect of altering the motor output.
EXPERIMENT 1

Introduction

In Experiment 1, the changing contribution of visual information to the planning and control of a movement over the course of learning was investigated. The paradigm tested the opposing predictions of Schema theory (Schmidt, 1975), that the influence of sensory information decreases with learning (see also Fitts & Posner, 1967), and the specificity of motor learning hypothesis. In addition, this experiment further tested the specificity of motor learning hypothesis by using a movement of increased duration and complexity compared to the pointing tasks previously used in these learning studies.

Subjects in three groups were asked to practise a movement that was comprised of a series of flexions and extensions about the elbow. One group, the control group, practised this movement for 300 trials with visually presented on-line kinematic feedback. Two other groups practised the same movement without the on-line kinematic feedback for 50, the low practice (LP) group, or 300 trials, the high practice (HP) group. Pretests and posttests were performed by all groups with the benefit of the on-line kinematic feedback. It was predicted that the control group would show no difference in performance in the transition from practice to the posttest. It was also predicted that the LP group would be able to make use of the on-line kinematic feedback in the posttest, and therefore improve their performance in the posttest relative to the end of practice. Finally, it was predicted that the HP group would suffer performance decrements in the transition to the posttest, as they would have already built up a well defined sensorimotor representation of the movement without the benefit of the on-line kinematic feedback. The addition of the feedback would then be inconsistent with how the HP group learned the task, and a reorganization of the existing sensorimotor representation would have to occur. During this period of reorganization, performance of the movement would be worse in the posttest than at the end of practice.
This experiment was designed to parallel Proteau et al. (1992). In this previous study strong evidence was found for the specificity hypothesis as the addition of performance-relevant information (vision) was found to cause decreased performance after extensive practice (1200 trials) but not after moderate practice (200 trials). In the present experiment, it was hypothesized that the performance and the learning of the movement would benefit from the inclusion of visually presented on-line kinematic feedback, which matched the visually presented kinematic criterion for the movement. Thus, in the posttest, if this additional, helpful information caused performance deterioration, than a strong argument for specificity would have been made. On the other hand, even if the feedback is not shown to be beneficial, the results could still support the specificity hypothesis if the HP group suffers performance decrements in posttest to a greater extent than the LP and control groups.

Methods

Subjects

30 self-proclaimed right-handed subjects participated (mean age: 20.0 years). Half of the subjects were female (mean age: 19.93), and were equally distributed between the groups with the 15 male subjects (mean age 20.07). Subjects were all students or recent graduates of Simon Fraser University. All subjects filled out informed consent forms and were paid $5 per hour for their time. Thirty-two subjects were tested in all, but the data for two had to be discarded due to these subjects' inability to correctly initiate the movement for a criterion number of trials. Specifically, subjects were required to initiate the movement properly in at least 70% of the pretest and posttest trials, and 80% of the practice trials. This was undertaken to ensure that there would be sufficient trials in each 10 trial block to compute means.
Apparatus

A manipulandum, which had a potentiometer (Heipot model 5617-109-1) positioned at the end of a shaft such that it could detect the angular position of the elbow, was used to measure the movement information. The manipulandum was positioned to the left of the subjects' seated position, and the height of the manipulandum was adjusted to accommodate the varied sitting heights of the subjects. This allowed the arm position to be held constant for all subjects, which was the arm flexed at the elbow and the arm abducted from the body such that the forearm was supported parallel to the ground and approximately 30° below the level of the shoulder. In-house software was used to control the presentation of the criterion curve, calculate the root-mean-square error (RMSE) that was used as feedback, and collect the raw position data. The analogue data was sampled from the potentiometer at 50 Hz. Fifty hertz was chosen as it allowed the proper sampling of the movement (the highest meaningful frequency in the movement was approximately 7 Hz, therefore the movement should be sampled at a minimum of 14 Hz) and afforded a reasonably high temporal resolution for the subsequent data analyses. Sampling rate was controlled by an external timing source (Hewlett-Packard 3310A Function Generator). The display-collection program was run on a 486 microcomputer with a full colour monitor (14" diagonal), from which subjects were positioned approximately 0.75 m distant.

Procedure

Upon arrival to the experimental chamber subjects were each given an information sheet to read, which provided the information necessary to complete the experiment. Verbal descriptions of the trials and how to complete them were also provided. To familiarize subjects with the apparatus and how their movements would be depicted on the screen, 10 initial trials were provided, in which subjects were directed to explore the potential movements and the apparatus. These trials were identical to the practice trials, except that all subjects had the on-line kinematic feedback and were shown only a
horizontal line in place of the criterion curve. Subjects received no coaching to aid their performance, but had to learn the characteristics of the apparatus and the display on their own.

The movement that subjects practised was a series of flexions and extensions about the elbow joint. The movement was specified spatially by the equation $-[\sin(0.5x) + \sin x + \sin(2x)]$, and had a duration of 2.2 seconds (see Figure 1). A summation of three sinusoids provides an irregular form that is useful in studying perceptual and cognitive processes used in the production of movement (Yamashita, 1990).

![Figure 1. The criterion curve. A peak to peak angular displacement of approximately 40° as well as a total of four joint reversals were required to produce the movement. In contrast to pointing movements, this movement required moment to moment spatial and temporal accuracy.](image)

Each trial had three phases. In the first phase the criterion was displayed on the monitor as a red waveform for 1.5 seconds. The red curve was always the same (Figure 1). The presentation and removal of this image was nearly instantaneous. The second phase began when the criterion curve was cleared from the screen. In this phase, subjects were to wait at least one second after the blanking of the monitor before moving. Upon
moving 2° in either direction the drawing of a line at a constant rate horizontally across the screen was triggered. When this green line reached the right hand side of the monitor the movement was ended, and collection was terminated. Thus subjects were aware that the movement had to be completed before the green line traversed the screen. Subjects performed the movement under two conditions: augmented, concurrent visually presented kinematic feedback and no visual feedback. In the former case, a green line was drawn on the monitor that represented the movements of the subject, affording on-line corrections based on this visual feedback. In the no visual feedback conditions, subjects were instructed to continue to direct their gaze at the monitor, even though it remained blank. In all cases the movement duration was 2.20 seconds. In the final phase of each trial, subjects were shown the criterion curve and subject produced curve superimposed on the monitor, as well as a numerical score (RMSE) for feedback. The temporal delay inherent in the visual representation of the feedback was approximately 20 msec. as a result of the screen refresh rate. This delay was greater than the time required to read the potentiometer and draw the pixel to the screen, which was dependent upon the rate at which the pixels were drawn across the screen (lag to read potentiometer equals \[20 \text{msec.} / \text{[number of pixels drawn per 20 msec.]}\]).

All subjects performed with the visually presented kinematic feedback during 10 pretest and 10 posttest trials. The control group performed 300 practice trials with the on-line kinematic feedback. The two experimental groups practised without the on-line visual feedback, the HP group performed 300 practice trials and the LP group performed 50 practice trials. Subjects were naive to the fact that their ability to perform the movement would be evaluated with the posttest trials. Two minute breaks were provided between the pretest and practice trials, and between the practice and posttest trials.

The experiment was self-paced, allowing subjects to proceed through the trials at a comfortable, individual pace. Rest breaks were encouraged, and could be taken by the
subjects at any time. The sessions for the HP and control groups took between 65 and 110 minutes, while the session for the LP group took 20 to 40 minutes.

**Data Treatment**

The analogue position data were sampled by a 486 microcomputer at 50 Hz. These data were then transformed into a format compatible with the laboratory's in-house analysis software on a Sun network. The displacement data were filtered at a high cut-off frequency of 7 Hz using a second order dual pass Butterworth filter. Each trial was visually inspected. If, as a result of this inspection, it was determined that the subject started the movement prematurely or from the incorrect initial position, the trial was discarded (it was impossible to reliably distinguish between these two scenarios). From the displacement data four dependent variables were calculated. First, RMSE (degrees) was calculated for each trial as a measure to compare the movement the subjects made with the criterion movement. In addition, cross correlations (no temporal shift), maximum cross correlation, and the corresponding temporal shifts (of the criterion movement over the subject produced movement) were calculated to yield information regarding overall, spatial, and temporal performance, respectively. This temporal measure is known as Tau (msec.). The curves were compared over 20 msec. increments for 20 steps in either direction (± 400 msec.).

RMSE and cross correlation values were computed as gross, overall indicators of level of performance.

All ANOVAs were performed using BMDP (8v). RMSE data was transformed by taking the natural log of the data, to make the distribution more normal, and thus suitable for statistical analyses. All main effects were further investigated using Tukey's HSD procedure (at α=.05 ). When a trial was discarded it was replaced by the mean value for that block of ten trials. This prevented any problems in running the statistical analyses with missing data. For analyses of the variability, the within subject standard deviations (SDs) were calculated over blocks of trials without replacing the missing data and using the
appropriate N for that block. In this way, the SD was not artificially lowered by the inclusion of the block mean as a trial.

Due to the nature of the questions being investigated, only portions of the data were analysed. The pretest trials were analysed to establish that the groups were not different in their initial performance with on-line feedback. The first ten practice trials allow the exploration of the immediate effect of the experimental conditions on performance. The final ten practice trials were taken to indicate maximum performance for the groups, which provided an indication as to the extent of the improvement differences between the groups. The posttest trials provide information regarding the effect of performing the movement with on-line feedback after practice. To further investigate the effect of the posttest, the final 10 practice trials and the 10 posttest trials were split into 5 trial blocks and submitted to within groups repeated measures ANOVAs.

Results

The results are presented in five separate sections. First, results are presented which indicate that the three groups initially demonstrated equivalent performance. Second, analyses are presented to demonstrate that subjects did improve with practice. Then a section is devoted to initial performance in the practice trials. The fourth section investigates the differences in performance at the end of the practice session. The final section investigates the performance effects of the transfer to the posttest trials.

Equivalency of Initial Performance

All groups performed in the same condition for the 10 pretest trials. Analyses of this block of 10 trials then gave an indication of equivalence between the groups in the initial performance of the movement.

For each of the four dependent measures a repeated measures ANOVA was performed on the factor group. The results for the ANOVAs on the means are presented in Table 1. It can be seen that the groups did not differ in mean performance over the 10
pretest trials. Similarly, after repeated measures ANOVAs on the mean within subject SDs, no differences were found for the variability of performance (see Table 2).

**Table 1. Comparisons of mean performance measures in the pretest trials, including results of ANOVAs.**

<table>
<thead>
<tr>
<th>Measure</th>
<th>Groups</th>
<th></th>
<th></th>
<th>F(2,27)</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>In(RMSE)</td>
<td>Control</td>
<td>2.193</td>
<td>2.277</td>
<td>2.104</td>
<td>1.45</td>
</tr>
<tr>
<td></td>
<td>HP</td>
<td>0.619</td>
<td>0.594</td>
<td>0.683</td>
<td>0.63</td>
</tr>
<tr>
<td></td>
<td>LP</td>
<td>0.764</td>
<td>0.749</td>
<td>0.804</td>
<td>0.42</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.764</td>
<td>0.749</td>
<td>0.804</td>
<td>0.42</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.764</td>
<td>0.749</td>
<td>0.804</td>
<td>0.42</td>
</tr>
<tr>
<td>Tau (msec.)</td>
<td></td>
<td>83.267</td>
<td>50.943</td>
<td>57.556</td>
<td>0.91</td>
</tr>
</tbody>
</table>

Therefore, since the initial performance of this novel movement did not differ from group to group any subsequent differences found between the groups is likely due to the influence of the experimental manipulations.

**Table 2. Comparisons of mean within subject SDs of the performance measures in the pretest trials, including results of ANOVAs.**

<table>
<thead>
<tr>
<th>Measure</th>
<th>Groups</th>
<th></th>
<th></th>
<th>F(2,27)</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>In(RMSE)</td>
<td>Control</td>
<td>0.355</td>
<td>0.349</td>
<td>0.364</td>
<td>0.05</td>
</tr>
<tr>
<td></td>
<td>HP</td>
<td>0.349</td>
<td>0.330</td>
<td>0.310</td>
<td>0.11</td>
</tr>
<tr>
<td></td>
<td>LP</td>
<td>0.267</td>
<td>0.214</td>
<td>0.203</td>
<td>0.51</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.267</td>
<td>0.214</td>
<td>0.203</td>
<td>0.51</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.267</td>
<td>0.214</td>
<td>0.203</td>
<td>0.51</td>
</tr>
<tr>
<td>Tau (msec.)</td>
<td></td>
<td>126.183</td>
<td>150.667</td>
<td>138.966</td>
<td>0.47</td>
</tr>
</tbody>
</table>

**Improvement With Practise**

As this was a learning study it was important to establish that the groups improved during the practice session. Qualitatively, Figures 2 through 5 seem to suggest that all groups did improve with practice, as error scores tend to decrease and cross correlation scores to increase. In contrast, none of the groups clearly converged on a Tau of 0 seconds, which would have indicated neither lags nor leads, but properly timed
movements. To demonstrate learning over the practice trials, block analyses were performed on five blocks of 10 trials, regularly spaced throughout the practice session. For the control and HP groups, those blocks were composed of trials 1-10, 71-80, 151-160, 221-230, and 291-300. For the LP group the blocks were formed from trials 1-10, 11-20, 21-30, 31-40, and 41-50. For each measure a 3 group x 5 block repeated measures ANOVA was performed on the means as well as the mean within subject SDs. These results are presented in Tables 3a-c (means) and Tables 4a-c (mean within subject SDs).
Figure 2. Means from blocks of 10 trials over the course of the experiment for ln(RMSE). Errors decreased over the course of practice for all groups.
Figure 3. Performance curve for the overall performance measure cross correlation. All groups demonstrated improvement in performing the movement over the course of practice.
Figure 4. Mean maximum cross correlation for blocks of 10 trials.
Spatial performance of the movement increased across the practice trials.
Figure 5. Mean Tau values during the experiment. Negative values indicate the movement was performed too quickly (lead) and positive values indicate the movement was performed more slowly than prescribed (lags).
Table 3a. Mean values for main effect of group.

<table>
<thead>
<tr>
<th></th>
<th>Control</th>
<th>HP Group</th>
<th>LP Group</th>
</tr>
</thead>
<tbody>
<tr>
<td>ln(RMSE)</td>
<td>*</td>
<td>2.026†</td>
<td>2.157†</td>
</tr>
<tr>
<td>C.C.</td>
<td>*</td>
<td>0.749</td>
<td>0.709†</td>
</tr>
<tr>
<td>Max. C.C.</td>
<td></td>
<td>0.866</td>
<td>0.840</td>
</tr>
<tr>
<td>Tau (msec.)</td>
<td>37.16</td>
<td>16.67</td>
<td>48.03</td>
</tr>
</tbody>
</table>

* Significant difference.
† Significantly different than the control group.

Table 3b. Mean values for main effect of block.

<table>
<thead>
<tr>
<th></th>
<th>Block</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
</tr>
<tr>
<td>ln(RMSE)</td>
<td>*</td>
</tr>
<tr>
<td>C.C.</td>
<td>*</td>
</tr>
<tr>
<td>Max. C.C.</td>
<td>*</td>
</tr>
<tr>
<td>Tau (msec.)</td>
<td>*</td>
</tr>
</tbody>
</table>

* Significant difference.
† Significantly different than block 1.
‡ Significantly different than block 2.

For the measure ln(RMSE), the results of the ANOVA on the block means indicated a significant group effect, $F(2, 18)=15.35, p<.0001$, which was the result of the control group performing with less error than the LP or HP groups. A main effect was also found for block, $F(4, 36)=51.82, p<.0001$, indicating that combined the groups performed with more error in the first block than for all other blocks, and in the second block with more error than the final 3 blocks. These two main effects must be interpreted in light of their significant interaction, $F(8, 72)=3.71, p<.0025$. As displayed in Table 3c, the three groups improved at different rates throughout these 5 blocks of practice. The LP group performed in the first block with more error than their final block of practice, while the HP and control groups were worse in their first block of practice than for all others, indicating that the majority of the error reduction was completed in the first 70 trials.
Table 3c. Block means for all measures for the 5 blocks of practice for each group (group by block interaction).

<table>
<thead>
<tr>
<th>Group</th>
<th>Block</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>2.041</td>
<td>1.680</td>
<td>1.509</td>
<td>1.514</td>
<td>1.451</td>
</tr>
<tr>
<td></td>
<td>ln(RMSE)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>C.C.</td>
<td>*0.755</td>
<td>0.907</td>
<td>0.928</td>
<td>0.935</td>
<td>0.937</td>
</tr>
<tr>
<td></td>
<td>Max. C.C.</td>
<td>*0.822</td>
<td>0.935</td>
<td>0.965</td>
<td>0.967</td>
<td>0.962</td>
</tr>
<tr>
<td></td>
<td>Tau (msec.)</td>
<td>37.77</td>
<td>24.04</td>
<td>45.05</td>
<td>46.40</td>
<td>32.21</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2.554</td>
<td>2.072</td>
<td>1.890</td>
<td>1.807</td>
<td>1.808</td>
</tr>
<tr>
<td></td>
<td>ln(RMSE)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>C.C.</td>
<td>*0.401</td>
<td>0.809</td>
<td>0.815</td>
<td>0.846</td>
<td>0.873</td>
</tr>
<tr>
<td></td>
<td>Max. C.C.</td>
<td>*0.648</td>
<td>0.910</td>
<td>0.905</td>
<td>0.921</td>
<td>0.945</td>
</tr>
<tr>
<td></td>
<td>Tau (msec.)</td>
<td>53.08</td>
<td>10.11</td>
<td>11.89</td>
<td>-1.51</td>
<td>9.80</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2.307</td>
<td>2.244</td>
<td>2.148</td>
<td>2.076</td>
<td>2.012</td>
</tr>
<tr>
<td></td>
<td>ln(RMSE)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>C.C.</td>
<td>*0.567</td>
<td>0.630</td>
<td>0.740</td>
<td>0.779</td>
<td>0.831</td>
</tr>
<tr>
<td></td>
<td>Max. C.C.</td>
<td>0.767</td>
<td>0.796</td>
<td>0.863</td>
<td>0.878</td>
<td>0.895</td>
</tr>
<tr>
<td></td>
<td>Tau (msec.)</td>
<td>90.53</td>
<td>55.69</td>
<td>46.13</td>
<td>43.27</td>
<td>4.53</td>
</tr>
</tbody>
</table>

* Significant difference.
† Significantly different than block 1.
‡ Significantly different than block 2.

Significant group, F(2, 18)=3.94, p<.05, and block, F(4, 36)=40.50, p<.0001, effects were also found for the cross correlation measure, with the results indicating that the control group was better than the LP group, and that the first block of practice was inferior to all others, while the second block was inferior to the last, respectively. The interaction, F(8, 72)=3.96, p<.001, indicated that the LP group's first block was different from the fourth and final blocks and that the final block was also different from the second. In addition, the first block for the HP group differed from all others, and the control group's final block was better than their first.

The measure of spatial performance, maximum cross correlation, yielded a significant block effect, F(4, 36)=30.39, p<.0001, as well as a group by block interaction, F(8, 72)=2.93, p<.01. The block effect was a result of the first block differing from all
others. The interaction indicated that the HP groups first block had a lower mean maximum cross correlation than the other blocks, and that the first block was different than the last three for the control group. The factor group yielded a nonsignificant result, $F(2, 18)=2.76, p>.09$.

The results of mean Tau value indicated only a block effect, $F(4, 36)=3.37, p<.02$, which was the result of the first block having a greater lag than the final block. The factor group and the interaction of group and block did not yield significant results, $F(2, 18)=1.01, p>.38$ and $F(8, 72)=1.26, p>.27$ respectively.

For each measure and each group the mean within subject SDs are presented in Tables 4a-c. The mean within group SDs for the measure $\ln$(RMSE) yielded no significant results, $F(2, 18)=0.82, p>.45$ for group, $F(4, 36)=1.66, p>.18$ for block, and $F(8, 72)=1.52, p>.16$ for the interaction. The mean within subject SDs for cross correlation yielded main effects for group, $F(2, 16)=6.84, p<.01$, and block, $F(4, 36)=13.46, p<.0001$, indicating that the control group performed with more consistency than either the HP or LP groups, and that the first block of practice had a greater mean within subject SD than the other blocks, respectively. The group by block interaction, $F(8, 72)=2.44, p<.025$, indicated that the HP group performed with less consistency in the first block than all others, and that the control group performed with more consistency in the final two blocks than the for the first. The decrease in mean within subject SD from the first to the fifth block for the LP group just failed to reach significance.

The mean within subject SDs for maximum cross correlation yielded a block effect, $F(4, 36)=13.19, p<.0001$, which was the result of the first block being different from all others. The group by block interaction, $F(8, 72)=2.31, p<.05$, indicated that the first block for both the HP and control groups was more variable than the others. The group effect was not significant, $F(2, 18)=3.06, p<.08$. 

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Timing variability provided main effects for group, $F(2, 18)=7.79, p<.005$, and block, $F(4, 36)=11.57, p<.0001$. These effects were the result of the control group performing with more consistency than the HP or LP groups, and block 1 being different from all others, respectively. The significant interaction, $F(8, 72)=2.37, p<.05$, indicated that the variability in the first block was higher than all other blocks for the HP group.

Table 4a. Mean within subject SD values for main effect of group.

<table>
<thead>
<tr>
<th></th>
<th>Control</th>
<th>HP Group</th>
<th>LP Group</th>
</tr>
</thead>
<tbody>
<tr>
<td>ln(RMSE)</td>
<td>0.250</td>
<td>0.277</td>
<td>0.256</td>
</tr>
<tr>
<td>C.C.</td>
<td>* 0.063</td>
<td>0.160†</td>
<td>0.164†</td>
</tr>
<tr>
<td>Max. C.C.</td>
<td>0.101</td>
<td>0.087</td>
<td>0.045</td>
</tr>
<tr>
<td>Tau (msec.)</td>
<td>* 51.45</td>
<td>105.36†</td>
<td>118.60†</td>
</tr>
</tbody>
</table>

* Significant difference.
† Significantly different than the control group.

Table 4b. Mean within subject SD values for main effect of block.

<table>
<thead>
<tr>
<th></th>
<th>Block</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
</tr>
<tr>
<td>ln(RMSE)</td>
<td>0.236</td>
</tr>
<tr>
<td>C.C.</td>
<td>* 0.214</td>
</tr>
<tr>
<td>Max. C.C.</td>
<td>* 0.146</td>
</tr>
<tr>
<td>Tau (msec.)</td>
<td>* 142.31</td>
</tr>
</tbody>
</table>

* Significant difference.
† Significantly different than block 1.
‡ Significantly different than block 2.
Table 4c. Mean within subject SDs of the performance measures across practice (group by block interaction).

<table>
<thead>
<tr>
<th>Group</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>Control</td>
<td>In(RMSE)</td>
<td>0.240</td>
<td>0.238</td>
<td>0.312</td>
<td>0.240</td>
</tr>
<tr>
<td></td>
<td>C.C.</td>
<td>*</td>
<td>0.140</td>
<td>0.053</td>
<td>0.054</td>
</tr>
<tr>
<td></td>
<td>Max. C.C.</td>
<td>*</td>
<td>0.122</td>
<td>0.039†</td>
<td>0.021†</td>
</tr>
<tr>
<td></td>
<td>Tau (msec.)</td>
<td>85.83</td>
<td>47.85</td>
<td>45.45</td>
<td>39.38</td>
</tr>
<tr>
<td>HP</td>
<td>In(RMSE)</td>
<td>0.227</td>
<td>0.262</td>
<td>0.267</td>
<td>0.303</td>
</tr>
<tr>
<td></td>
<td>C.C.</td>
<td>*</td>
<td>0.303</td>
<td>0.141†</td>
<td>0.120†</td>
</tr>
<tr>
<td></td>
<td>Max. C.C.</td>
<td>*</td>
<td>0.189</td>
<td>0.059†</td>
<td>0.067†</td>
</tr>
<tr>
<td></td>
<td>Tau (msec.)</td>
<td>198.95</td>
<td>85.53†</td>
<td>89.09†</td>
<td>81.80†</td>
</tr>
<tr>
<td>LP</td>
<td>In(RMSE)</td>
<td>0.240</td>
<td>0.239</td>
<td>0.279</td>
<td>0.257</td>
</tr>
<tr>
<td></td>
<td>C.C.</td>
<td>0.198</td>
<td>0.196</td>
<td>0.164</td>
<td>0.151</td>
</tr>
<tr>
<td></td>
<td>Max. C.C.</td>
<td>0.127</td>
<td>0.117</td>
<td>0.095</td>
<td>0.091</td>
</tr>
<tr>
<td></td>
<td>Tau (msec.)</td>
<td>142.14</td>
<td>144.33</td>
<td>122.96</td>
<td>100.78</td>
</tr>
</tbody>
</table>

* Significant difference.
† Significantly different than block 1.

Therefore, it appears clear that all groups demonstrated some significant trends towards improved performance and decreased variability over the course of practice.

**First Practice Block: Effect of the On-Line Feedback**

Comparing the groups' performance during the first 10 practice trials gives an indication of how the absence of the on-line feedback affected the HP and LP groups. The previous analyses (3 group x 5 block repeated measures ANOVAs) allow this comparison by looking only at the first block of the group by block interactions. The mean data are presented in Table 3c. and the mean within subject SD results in Table 4c under the Block 1 columns. (F and p values were reported in the previous section.)

The results of the group by block interaction for the mean of ln(RMSE) indicates that the control group performed in the first ten practice trials with less error than the HP group. Similarly, for mean maximum cross correlation, the control group was again better
than the HP group. For mean cross correlation, the control group was superior over the first 10 trials to either the LP or HP group, while the groups did not differ for mean Tau. The mean within subjects SD for cross correlation indicated that the HP group differed from the control and the LP groups. The variability for Tau was also higher for the HP group than the control group.

Thus, the first 10 practice trials indicate the superiority of the control group initially, and hint at the idea that the performance of the movement benefits almost immediately from the presence of the on-line kinematic feedback.

**Final Practice Block: Effect of On-Line Feedback and Amount of Practise**

If, as hypothesized, more practice will result in better performance, and if having the visually presented on-line kinematic feedback is beneficial to performance, then at the end of practice the control group should perform better than the HP group, which should, by virtue of amount of practice, perform better than the LP group.

This prediction was tested using the results of the 3 group x 5 block repeated measures ANOVAs to compare the mean and mean within subject SDs values over the final block of 10 trials (F and p values were reported in the section on the block analysis). The data and the results of these ANOVAs are presented in Table 3c and Table 4c, under the Block 5 columns.

Neither the mean nor mean within subject SD results for cross correlation, maximum cross correlation, or Tau differentiated the groups over the last 10 practice trials. However, the results for mean ln(RMSE) indicated that the control group was superior to the HP and LP groups. The mean within subject SD for ln(RMSE) yielded no differences.

Even though many of the differences are non-significant, the predicted trend is clearly evident in all the dependent variables except the temporal measure.

Therefore, the evidence that greater amounts of practice led to superior performance is not unequivocal. Likewise, the hypothesized benefits of the on-line kinematic feedback
were not supported by the statistical analyses. Qualitatively, however, it is evident from Figures 2 through 4 that the on-line kinematic feedback was helpful and that more practice led to better performance. More unequivocal results may have been obtained if the LP group had performed fewer practice trials, or if the movement itself was more demanding. This will be discussed again in the discussion.

The Transition to the Posttest

Over the final 10 practice trials, the trend for performance indicated that the control group demonstrated superior performance while the LP group demonstrated the worst performance. It was of interest to see if that trend changed when the on-line feedback was provided to the LP and HP groups in the 10 posttest trials. Indeed, these trend reversals, the LP group performing better than the HP group in the posttest, is what was found, as is evidenced in Figure 6.

To examine the effect of the transfer to the posttest, 3 group x 2 period x 2 block repeated measures ANOVAS were performed on the means and the mean within subject SDs for each measure. The periods were defined as the final 10 trials of practice and the 10 posttest trials, while the blocks were two blocks of 5 trials within each period. By considering only the second period, the differences between the groups during the posttest trials can be investigated. Then, considering the entire set of analyses, the effect of the transition from the end of practice to the posttest was investigated.

To investigate the relationship between the different groups' performance, the second period in all group by period interactions was specifically examined (the results of the ANOVAs are presented later, when the transition itself is evaluated). Post hoc analyses on the significant group by period interaction for the measure mean ln(RMSE) indicated that the control group performed in the posttest with less error than either the HP or the LP groups. In the posttest the HP group was found to have a lower maximum cross correlation than the control group. For the measure Tau, the HP group differed from both the control
and the LP groups, as the HP group led the criterion while the other groups lagged. The only significant result from the mean within subject SDs was for maximum cross correlation, in which the HP group was found to be more variable than the control group.

To summarize, in the posttest, the control group performed better than the other two groups, and the temporal ability of the HP group was different than either the LP or control groups. The results for the means are depicted in Figure 6.
Figure 6. Between group comparisons of relative end of practice and posttest performance. The reversal of performance ranking for the HP and LP groups from 2nd and 3rd at the end of practice (crosses) to 3rd and 2nd in the posttest (filled circles), respectively, is evident. A. ln(RMSE). B. Cross Correlation. C. Maximum Cross Correlation. D. Tau.
Figure 7. The effect of transition from practice to posttest as indicated by the mean taken over blocks of 5 trials. A. ln(RMSE). B. Cross Correlation. C. Maximum Cross Correlation. D. Tau.

By now considering all the data and the full results of the 3 group by 2 period by 2 block repeated measures ANOVAs, the effect of the transition from the end of practice to
the posttest can be investigated. Of primary interest here are the group, group by period, and group by period by block effects. These data are presented in Figure 7, where the mean values for the three way interaction are presented, and in Table 5, where the mean within subject SDs are presented.

Main effects for group were found for two of the mean dependent measures, while the difference among the groups was marginal for cross correlation, $F(2, 18)=3.34, p<.06$, and maximum cross correlation, $F(2, 18)=3.31, p<.06$. The significant group effects resulted from the control group performing in the transition with less error than the LP or HP groups, $F(2, 18)=10.85, p<.001$, and the HP group leading the criterion instead of lagging it, $F(2, 18)=12.52, p<.0005$.

A significant group by period interaction was found for the measure $\ln\text{(RMSE)}$, $F(2, 18)=4.41, p<.05$, which resulted from the control group performing with less error in both periods than the other groups. The group by period interaction from the measure maximum cross correlation, $F(2, 18)=6.95, p<.01$, resulted from the posttest performance of the HP group being worse than the HP group's end of practice performance, as well as the performance in both periods by the control group. Similarly, the HP group performed with significantly different temporal ability in the posttest period compared to the performance of the control group in both periods as well as the performance of the LP group in the posttest, $F(2, 18)=4.64, p<.025$. The group by period interaction approached significance for the measure cross correlation, $F(2, 18)=2.93, p<.08$.

The group by period by block interactions for the means were all nonsignificant: For the measure $\ln\text{(RMSE)}$, $F(2, 18)=0.25, p>.77$, cross correlation, $F(2, 18)=0.18, p>.83$, maximum cross correlation, $F(2, 18)=0.48, p>.62$, and Tau, $F(2, 18)=0.20, p>.82$. 

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The mean within subject SDs yielded significant effects for the factor group for ln(RMSE), $F(2, 18)=5.13, p<.025$, cross correlation, $F(2, 18)=5.45, p<.025$, and Tau, $F(2, 18)=4.59, p<.025$, but not for maximum cross correlation, $F(2, 18)=2.95, p<.09$, although this nearly reached conventional levels of significance. The group effects for ln(RMSE) and cross correlation were the result of the control group being less variable in performance than the HP group, while the group effect for Tau was a result of the control group differing from both the LP and HP groups.

The group by period interaction reached significance for the mean within subject SDs of maximum cross correlation, $F(2, 18)=4.58, p<.025$. This is the result of the HP group being more variable in the posttest than the control group in either period, and the LP group having higher variability at the end of practice than the control group in either period.
The other measures failed to yield a group by period interaction [ln(RMSE): $F(2, 18) = 1.18, p > .32$; cross correlation: $F(2, 18) = 0.85, p > .44$; and Tau: $F(2, 18) = 0.48, p > .62$].

As with the means, the three way interactions did not reach significance for any of the mean within subject SDs of the measures: ln(RMSE), $F(2, 18) = 0.86, p > .43$; cross correlation, $F(2, 18) = 0.31, p > .74$; maximum cross correlation, $F(2, 18) = 0.31, p > .74$; and Tau, $F(2, 18) = 0.06, p > .93$.

Therefore, evidence was found in these analyses for the specificity hypothesis. The control group, performing in the posttest under the conditions that they had practised, showed no decrement in performance of the movement in the transition from the end of practice to the posttest. The HP and LP groups, performing under different conditions than they had practised, showed a decrease in performance in the posttest and signs of being better in the posttest, respectively.

**Discussion**

The purpose of this experiment was to determine if the influence of sensory information decreases with learning, as proposed by a number of researchers, or if performing the movement in different sensory conditions than when the movement was learned would be detrimental to performance, as predicted by the specificity of motor learning hypothesis. Thus, it was predicted that the HP group would demonstrate decreased performance in the posttest relative to practice, while the LP group's performance would not change or could even improve, and the control group maintain performance in accordance with the specificity of motor learning hypothesis. These predictions were largely upheld.

From equivalent performance in the pretest, all three groups showed improvement with practise. Although failing to reach significance, the groups achieved predictable end of practice performance rankings: Practising with the on-line kinematic feedback appeared
to result in superior performance than practising without it and more practise tended to lead to better performance. Thus, at the end of practice the control group was superior to the HP group, which was better than the LP group. This indicates that having the on-line feedback should be helpful and improve performance, but only if the subjects are able to utilise this information. It appeared that the LP group could utilise this new feedback in the posttest, as their limited experience at the task resulted in an unrefined and poorly defined sensorimotor representation of the movement. Thus, this "fuzzy" representation was flexible enough to be rapidly modified to accommodate the use of the novel visual information. For the HP group, in contrast, the sensorimotor representation was more sharply defined and more highly refined as a result of the increased level of practise. When the on-line visual information was introduced it did not match the on-line information that had previously been used to control the movement (proprioception), and caused performance disruptions while the existing sensorimotor representation was modified to accommodate the new information.

This period required for the modification of the sensorimotor representation to allow the use of the information afforded by the visually presented on-line kinematic feedback by the HP group was surprisingly short, less than ten trials (see Figure 8). One explanation for these results is that it is possible that the subjects were not as extensively practised as in previous studies (e.g. Proteau et al., 1992) where a more long-lasting performance decrement was seen in the posttest condition where vision was provided. Thus the subjects' sensorimotor representations were not extremely well formed after 300 practise trials, allowing for the necessary modifications to be made to the sensorimotor representation in a matter of trials. The present results, however, do not necessarily speak against the specificity hypothesis. The fact that the time course of the reorganization in the posttest was almost immediate for the LP group while it took a number of trials for the HP
group is still evidence for this theoretical position. The time course of this modification and how it is related to the extent of practice warrants further investigation.

Figure 8. Mean trial RMSE data for the HP group in the posttest. The trend is for a return back to end of practice performance after only 10 trials in the posttest, arguing for the transient nature of the reorganization of the sensorimotor representation. The equation for the best fit line is $y=2.11-0.02x$.

It is interesting to note that while the HP group suffered decreases in the spatial aspects of the movement's performance, the temporal aspects of the performance changes were more dramatic. As is evidenced in Figure 5 the HP group showed a weak trend to lead the criterion, but this group seemed to vary around the point of zero lag. With no on-line temporal information to help guide the timing of the movement this is not very surprising. However, when given the on-line visually presented kinematic feedback, the tendency to lead the criterion was strong. A similar observation was made while testing the subjects, as performance of the movement in the transition from the pretest to the practice trials subjects in both the HP and LP groups demonstrated a short term tendency to perform the movement very slowly. This lag of the criterion was 40 to 120 msec in the first ten practice trials. Thus, on-line visual information that provides temporal information (as the
on-line kinematic feedback provided here did) was not initially properly used by the HP subjects in the posttest.

In previous experiments using the same apparatus and similar conditions (Barnford, 1985; Romanow, 1984), subjects displayed the tendency to lag the criterion when the on-line feedback was visually presented. In the present experiment, the control group seemed to reach a plateau of between 20 and 40 msec. of lag. This is likely the result of the inherent delay in the presentation of information on a computer screen. The display program used in this experiment updates the visual display every 20 msec. (based on the screen refresh rate). Thus, it may be unsurprising to see such timing performance when the feedback provided to them to aid in the control of the temporal aspects of the movement had inherent lags. However, the presence of this lag in the presentation of the on-line visual feedback does not preclude performance with proper timing.

The lack of strong statistical support for the benefits of the on-line kinematic feedback weakens the analogy attempted to Proteau et al. (1992), where the addition of vision that was beneficial to the task was disruptive if subjects practiced the movement without vision. It seems that in the present experiment the LP group may have been allowed too many practice trials, as they achieved a final practice performance that was similar to that of the HP and control groups. If the movement had been more difficult to perform and learn, the LP group would not have reached the near-plateau performance of the other two groups after 50 trials (the HP and control groups demonstrated no significant improvements in performance after trial 70). Conversely, the LP group could have performed fewer trials of the movement used in this experiment. This shortcoming of this experiment, that the LP and HP groups may not have reached clearly different end of practice performance levels, does not detract from its usefulness as a test of the specificity of motor learning hypothesis, as relatively different practise and learning was still achieved between the groups.
In the present experiment, even though the evidence for the benefits of the on-line kinematic feedback are weak, the decrease in ability to perform the movement correctly early in the posttest by the HP group and the improvement of the LP group in posttest relative to the end of practice supports the specificity hypothesis, as it was in Proteau et al. (1987) when vision was removed. Regardless, even if the on-line kinematic feedback was not reliably beneficial to performance, it offered a novel sensory experience for the HP and LP groups in the posttest, which is all that is required in paradigms testing the specificity hypothesis.

The results of Experiment 1 provide further support for the specificity of motor learning hypothesis. This experiment yielded similar results to those previously reported as evidence for specificity in motor learning (e.g. Proteau et al., 1987; Proteau et al., 1992). The differential performance of the HP and LP groups in the posttest relative to practice indicated that the sensory information did not decrease in importance as learning progressed, which is contrary to the predictions of Schema theory (Schmidt, 1975), the stages of learning proposed by Fitts and Posner (1967), and the theory of learning proposed by Abbs and colleagues (1984). In addition to supporting the specificity hypothesis, the hypothesis is extended, as it was shown to apply not only to rapid pointing movements, but also to the longer, more complex movement used in this experiment.

The temporal aspect of the movement and the duration of the performance decrement related to the reorganization of the sensorimotor representation in the posttest were further investigated in Experiment 2.
EXPERIMENT 2

Introduction

Previous experiments (e.g. Adams et al., 1972; Proteau et al., 1987; Proteau et al., 1992), including experiment 1, have found evidence that the performance of a movement is specific to the sensory conditions under which it was learned, and that this specificity increases with increased levels of practise. The assumption of a sensorimotor representation being constructed over learning that causes this specificity leads to a similar prediction regarding the motor output of a learned movement. Explicitly, since the performance of a learned movement appears to be specific to the sensory information encountered during learning, it may be that its performance is also specific to the motor output. To test this general hypothesis, the duration of a movement was changed after learning had occurred, and the time course of the modification of the movement towards the new duration was observed.

Manipulation of movement duration does not cause changes exclusively in the motor aspects of a movement. Proprioceptors that sense rate of change of muscle length (muscle spindles, group 1a afferents) and force (Golgi tendon organs, group 1b afferents) are also affected when movement duration is varied. However, if visual information, which has been shown to dominate proprioception and be used preferentially in the control of movement (Hay, Pick, & Ikeda, 1965; Smyth, 1978), remains constant throughout the changes in movement duration, the effect of changing the proprioceptive information should be negligible in comparison to the actual motor performance of the movement.

In addition to this manipulation of movement duration, the similarity of the new movement duration to that practised was also manipulated. Thus, the degree of similarity was expected, based in part on the phenomenon of stimulus generalization, to be related to the ability to perform the learned movement at a novel duration. This effect, also known as stimulus control, results in the decreasing probability of a response as the stimulus
becomes more unlike the original training stimulus (Lieberman, 1990). To illustrate this effect, pigeons trained to peck a button when a light of 580 nm. was illuminated decreased their pecking frequency as the wavelength of light got farther away from 580 nm., for example 600 and 620 nm., resulting in a probability of response profile that was single peaked at the training wavelength, and decayed in probability at increasingly higher or lower wavelengths (Lieberman, 1990). This graded generalization of responding has previously been demonstrated with different movement lengths for a linear positioning task (Dickinson & Hedges, 1986). Thus, in the context of the present experiment, subjects should have increasing difficulty adjusting to the new movement duration in the posttest as that duration gets increasingly dissimilar from the practised duration. This ancillary hypothesis, that a performance gradient based on movement duration similarity will exist within the specificity of learning context, is also investigated in this experiment.

Two competing predictions of the outcome of such a manipulation can be made, again pitting Schema theory against the specificity of motor learning hypothesis. While Schema theory’s generalized motor programs have a number of invariant features (e.g. relative force), one of the parameters that can vary is overall duration (Schmidt, 1988). Using this overall duration parameter, the speed with which a given motor program can be ‘played out’ can be changed to accommodate different situations without requiring a new program for each possible speed of execution. Support for this proposition comes from a number of sources. For example, Viviani and Terzuolo (1980) presented data indicating that in both typing and writing this constant relative phasing between the letters despite the total duration of the movement is evident. Thus, the components of the movement sequence maintained a constant relative duration (or, in the case of handwriting, a temporally scaled tangential velocity) over varying whole movement durations. Similarly, using a rotary sequential positioning task, Carter and Shapiro (1984) found evidence to support the prediction that the relative timing of the elements of a movement is maintained.
in the event of changes in the overall movement duration. It should be noted, however, that the simplistic interpretation of the bulk of the literature supporting the existence of an overall duration parameter has been criticized (Gentner, 1987). In any event, Schema theory would predict that a reasonably well formed generalized motor program would allow the parameterization of this overall duration parameter. This would lead to the prediction that the HP group, having formed a stronger Schema as a result of the amount of practice (Schmidt, 1975), would be quicker than the LP group in adjusting to the new duration.

The specificity of motor learning hypothesis, while recently applied to sensory information used to plan and control a movement, originated in the study of motor performance. Henry (1968) stated "motor skills and large muscle psychomotor abilities are far more specific than had previously been realized" (p. 329). Indeed, Bachman (1961) demonstrated that the performance and learning of one of two distinct balancing tasks afforded no transfer to the other. Similarly, in a multitarget sequencing task, Fischman and Lim (1991) found that transferring to a novel sequence (from one or two targets to three) resulted in interference in the performance of the three target task. While the authors attributed this effect to neural priming, the results are consistent with a specificity of learning notion. Thus, sufficient evidence exists that motor learning and performance of a movement can be specific to the movement practised to hypothesize that the learning of a movement’s duration is specific to the duration practised. More than simple parameterization of an overall duration parameter would be needed, then, as the sensorimotor representation of the movement would require modification to allow correct performance of the movement’s novel duration.

A number of hypotheses were tested in this experiment. First, it was predicted that by the end of the practice session subjects in the three HP groups would perform better, and would have learned the movement to a greater degree than the LP groups, as a function of amount of practice. Second, an increasing degree of specificity would be seen with
more experience at the practised movement duration. That is, the time course of the reorganization of the sensorimotor representation would be shorter in the posttest for the LP group than for the HP group. This prediction is the opposite of that of Schema theory, which would suggest that the HP group would have a better formed Schema, and would be better equipped than the LP group to parameterize overall duration to allow performance of the posttest movement duration. Finally, according to the specificity of motor learning hypothesis, the generalization gradient should be more evident for the HP group than for the LP group. The necessary modifications to the poorly formed sensorimotor representation of the LP group should not be appreciably different for the similar or dissimilar movement durations in the posttest. In contrast, the HP group’s more highly defined sensorimotor representation should require less recalibrating to accommodate the similar duration than for the dissimilar duration.

Methods

Subjects

Forty-two self-proclaimed right-handed subjects participated (mean age: 22.33 years). Twenty-four of the subjects were female (mean age: 22.46 years), and eighteen of the subjects were male (mean age 22.17). Subjects were volunteers from the student population of Simon Fraser University. All subjects filled out informed consent forms and were paid $5 per hour for their time. Forty-six subjects were tested in all, but the data for four had to be discarded due to two of these subjects’ inability to correctly initiate the movement for a criterion number of trials (see experiment 1) and the two other displayed no improvement in the performance of the movement over practise. None of the subjects tested in experiment 2 had participated in experiment 1.

Apparatus

The apparatus and experimental set up were identical to those employed in Experiment 1.
Procedure

As in experiment 1, upon arrival to the experimental chamber subjects were each given an information sheet to read, which provided the information necessary to complete the experiment. Verbal descriptions of the trials and how to complete them were also provided. To familiarize subjects with the apparatus and how their movements would be depicted on the screen, 10 initial warm up trials were provided, in which subjects were directed to explore the potential movements and the apparatus. These trials were identical to the practice trials, except that subjects were shown only a horizontal line in place of the criterion curve.

The movement that subjects practised was a series of flexions and extensions about the elbow joint, identical to that used in experiment 1 (see Figure 1).

Subjects had the on-line kinematic feedback visually presented on all trials. Subjects performed ten pretest trials and 20 posttest trials. This increase in the number of posttest trials over experiment 1 (from 10) was to attempt to further elucidate the time course of the reorganization of the movement representation that allowed the successful performance of the novel variant of the learned movement. All the practice trials intervening between the pretest and posttest were of 2.20 seconds in duration. Six groups of subjects were tested, with 7 subjects per group. Subjects were randomly assigned to one of the groups before testing began with the proviso that each group have 3 male subjects and 4 females. Half of the groups performed 300 practise trials (HP) while the remaining performed 50 (LP). For the three groups within each level of practise, one group performed movements in the pretest and posttest that were 2.20 seconds in duration (controls), while another group performed movements that were 2.64 seconds in duration (near), and the remaining group performed movements that were 3.30 seconds in duration (far). The movement duration was increased by slowing the rate at which the subject's feedback curve tranversed the monitor. Thus, two levels of practise trials by three (pretest)
posttest movement durations yielded the six groups. The procedures were otherwise exactly like those for the control group in experiment 1.

Data Treatment

The data were handled the same way as in experiment 1.

Results

As for the first experiment, the analyses were performed and are presented to answer a number of questions. First, did the groups begin the experiment with equivalent initial performance? Second, did the groups improve over practise, demonstrating learning? Third, in the pretest were there any performance differences? Fourth, did having more practise trials result in better final performance, and were there any other differences among the groups based on their pretest experiences? Fifth, what happened to performance in the posttest, especially in the transition from practice to posttest? Finally, the performance disruptions in the transition period were further analysed to investigate the hypothesis that performance degradation in posttest was related to the similarity of the posttest to the practice movement durations.

Equivalency of Initial Performance

It was important to establish that the six groups did not differ initially, to allow subsequent comparisons to be made without the spectre of initial performance bias. Since the pretest condition was not uniform for all groups, the first 10 practice trials were compared, as all groups practised a 2.20 second movement, to examine the possibility of initial performance differences between the groups.

The analyses of the first 10 practice blocks were embedded in the analyses designed to evaluate improvement in the performance of the movement over the course of practise. Thus, the lack of a practice level by posttest movement duration by block interaction, or the lack of a significant difference for at least the first block of these interactions, indicated that the groups began the experiment with equivalent ability to perform the movement. As less
discriminating factors, practise level by block as well as posttest movement duration by block interactions will also be considered, again only over the first block. The 2 practice level by 3 posttest movement duration by 5 block repeated measures ANOVAs are described in this section only as they pertain to the question of initial performance equivalency.

For mean ln(RMSE), the posttest movement duration by block interaction and the practice level by posttest movement duration by block interactions were nonsignificant, $F(8, 48)=1.49, p>.18$ and $F(8, 48)=0.83, p>.57$, respectively. The practice level by block interaction was significant, $F(4, 24)=9.11, p<.0001$, but the differences between the two levels of practice were not significantly different for the first block of practice. No significant results were obtained for the mean within subjects SDs for ln(RMSE): practice level by block, $F(4, 24)=0.58, p>.67$, posttest movement duration by block, $F(8, 48)=0.50, p>.85$, and practice level by posttest movement duration by block, $F(8, 48)=1.00, p>.44$.

A significant practice level by block interaction for mean cross correlations, $F(4, 24)=3.11, p<.05$, again yielded no difference between the levels of practice for the first block of practice. The posttest movement duration by block interaction and the practice level by posttest movement duration by block interactions were nonsignificant, $F(8, 48)=0.68, p>.70$ and $F(8, 48)=0.63, p>.74$, respectively. As for the mean within subject SDs for ln(RMSE), the mean within subject SDs for cross correlations yielded no significant effects of interest here: practice level by block, $F(4, 24)=1.26, p>.31$, posttest movement duration by block, $F(8, 48)=1.26, p>.31$, and practice level by posttest movement duration by block, $F(8, 48)=0.95, p>.48$.

Relevant results were found for neither the mean maximum cross correlation, practice level by block, $F(4, 24)=1.63, p>.20$, posttest movement duration by block, $F(8, 48)=0.86, p>.55$, and practice level by posttest movement duration by block, $F(8,
nor the mean within subject SD of the maximum cross correlation, practice level by block, $F(4, 24)=0.06, p>.99$, posttest movement duration by block, $F(8, 48)=0.85, p>.56$, and practice level by posttest movement duration by block, $F(8, 48)=1.14, p>.35$.

Similarly, no significant result relevant to the question of initial performance equivalency were found for mean $\tau$, practice level by block, $F(4, 24)=0.27, p>.89$, posttest movement duration by block, $F(8, 48)=0.52, p>.83$, and practice level by posttest movement duration by block, $F(8, 48)=0.47, p>.87$, nor the mean within subject SDs of $\tau$, practice level by block, $F(4, 24)=1.37, p>.27$, posttest movement duration by block, $F(8, 48)=0.73, p>.66$, and practice level by posttest movement duration by block, $F(8, 48)=1.55, p>.16$.

The results of these analyses clearly indicate that there was no difference in the performance of the movement in the first ten practice trials as a result of level of practice, which should have no bearing, as practice had just begun, or the duration of the movement experienced in the pretest. Thus, the groups did begin with equivalent initial performance levels, and any subsequent performance differences among the groups can be attributed to the experimental design.

**Improvement With Practise**

Figures 9 through 12 display the performance of the six groups averaged over blocks of 10 trials for the whole experiment.
Figure 9. ln(RMSE) blocked over ten trials for all phases of the experiment, demonstrating the improvement in performance that occurred with practise.
Figure 10. Changes in cross correlation values for all groups for the entire experiment. Cross correlations increased across the practice session for all groups.
Figure 11. Maximum cross correlation from pretest through practice and the posttest. Block means illustrate the improvement in performance with practice.
Figure 12. Tau values (msec.) for each group throughout the three phases of the experiment. Negative Tau values represent movements performed too quickly (leading the criterion) while positive Tau values represent movements performed too slowly (lagging the criterion).
Examination of Figures 9 through 12 demonstrate that all groups displayed a decrease in error and an increase in correlations with practise. As in experiment 1, however, the ability to perform the temporal aspects of the movement did not show a systematic improvement towards perfect timing (no leads or lags). As in the previous experiment, subjects tended to lag the criterion movement, but slightly more than that accounted for by the lag inherent in the display system (=20 msec.). In addition, the temporal performance was highly variable. To establish that the groups improved with practise, five equally spaced blocks within the practice session were compared. For the LP groups, these blocks of 10 trials were 1-10, 11-20, 21-30, 31-40, and 41-50. For the HP groups, these blocks were 1-10, 71-80, 151-160, 221-230, and 291-300. A series of 2 practice level by 3 posttest movement duration by 5 block repeated measures ANOVAs were performed to determine if improvement occurred with practise.

<table>
<thead>
<tr>
<th></th>
<th>LP</th>
<th>HP</th>
</tr>
</thead>
<tbody>
<tr>
<td>ln(RMSE)</td>
<td>M 1.768</td>
<td>1.582</td>
</tr>
<tr>
<td></td>
<td>SD 0.256</td>
<td>0.256</td>
</tr>
<tr>
<td>Cross Correlation</td>
<td>M * 0.864</td>
<td>0.909</td>
</tr>
<tr>
<td></td>
<td>SD * 0.092</td>
<td>0.059</td>
</tr>
<tr>
<td>Max. Cross Correlation</td>
<td>M * 0.927</td>
<td>0.958</td>
</tr>
<tr>
<td></td>
<td>SD * 0.057</td>
<td>0.030</td>
</tr>
<tr>
<td>Tau</td>
<td>M 39.83</td>
<td>47.11</td>
</tr>
<tr>
<td></td>
<td>SD 61.01</td>
<td>49.73</td>
</tr>
</tbody>
</table>

* Statistically significant effect.

The factor practice level yielded four main effects. The two for the block means were for the measures mean cross correlation, $F(1, 6)=6.01$, $p<.05$, and mean maximum cross correlation, $F(1, 6)=12.08$, $p<.025$. In both cases, the HP groups had higher cross correlations. The measure ln(RMSE) provided a marginal effect for practice level, $F(1,
and the trend was for the HP groups to perform with less error. The mean Tau values did not produce a practice level effect, $F(1, 6)=0.30, p>.60$, possibly as a result of the large variability. For the mean within subject SDs of these measures, SD $\ln$(RMSE), $F(1, 6)=0.00, p>.98$, and SD Tau, $F(1, 6)=3.91, p>.09$, did not produce significant effects, while SD cross correlation, $F(1, 6)=6.31, p<.05$, and SD maximum cross correlation, $F(1, 6)=11.21, p<.025$, did, indicating that for these two measures, mean within subject variability was greatest for the LP groups. Thus evidence does exist that over all the practice blocks, the HP groups perform better than the LP groups. These data are displayed in Table 6a.

Table 6b. Mean values for posttest movement duration from block analyses.

<table>
<thead>
<tr>
<th></th>
<th>2.20</th>
<th>2.64</th>
<th>3.30</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\ln$(RMSE)</td>
<td>M 1.674</td>
<td>1.715</td>
<td>1.635</td>
</tr>
<tr>
<td></td>
<td>SD 0.259</td>
<td>0.252</td>
<td>0.258</td>
</tr>
<tr>
<td>Cross Correlation</td>
<td>M 0.879</td>
<td>0.874</td>
<td>0.906</td>
</tr>
<tr>
<td></td>
<td>SD 0.080</td>
<td>0.076</td>
<td>0.070</td>
</tr>
<tr>
<td>Max. Cross Correlation</td>
<td>M 0.936</td>
<td>0.940</td>
<td>0.951</td>
</tr>
<tr>
<td></td>
<td>SD 0.045</td>
<td>0.044</td>
<td>0.040</td>
</tr>
<tr>
<td>Tau</td>
<td>M 32.66</td>
<td>57.31</td>
<td>40.43</td>
</tr>
<tr>
<td></td>
<td>SD 57.44</td>
<td>48.96</td>
<td>59.72</td>
</tr>
</tbody>
</table>

Posttest movement duration effects were not expected, as this would mean that the 10 pretest trials had an impact on performance during the test trials, and this expectation was upheld (see Table 6b). For the mean measures, no effects were found: $\ln$(RMSE), $F(2, 12)=1.03, p>.38$; cross correlation, $F(2, 12)=1.64, p>.23$; maximum cross correlation, $F(2, 12)=0.62, p>.55$; and Tau, $F(2, 12)=1.66, p>.23$. Similarly, no effects were found for the mean within subject SDs of the dependent measures: $\ln$(RMSE), $F(2, 12)=0.09, p>.91$; cross correlation, $F(2, 12)=0.38, p>.69$; maximum cross correlation, $F(2, 12)=0.15, p>.85$; and Tau, $F(2, 12)=1.99, p>.17$. 

65
Table 6c: Mean values for blocks from block analysis.

<table>
<thead>
<tr>
<th></th>
<th>Block 1</th>
<th>Block 2</th>
<th>Block 3</th>
<th>Block 4</th>
<th>Block 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>ln(RMSE)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>M</td>
<td>1.919</td>
<td>1.685†</td>
<td>1.625†</td>
<td>1.598†</td>
<td>1.548††</td>
</tr>
<tr>
<td>SD</td>
<td>0.255</td>
<td>0.265</td>
<td>0.253</td>
<td>0.266</td>
<td>0.243</td>
</tr>
<tr>
<td>Cross Correlation</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>M</td>
<td>0.815</td>
<td>0.893†</td>
<td>0.904†</td>
<td>0.904†</td>
<td>0.917†</td>
</tr>
<tr>
<td>SD</td>
<td>0.128</td>
<td>0.069†</td>
<td>0.061†</td>
<td>0.069†</td>
<td>0.050†</td>
</tr>
<tr>
<td>Max. Cross Correlation</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>M</td>
<td>0.906</td>
<td>0.945†</td>
<td>0.950†</td>
<td>0.951†</td>
<td>0.959†</td>
</tr>
<tr>
<td>SD</td>
<td>0.073</td>
<td>0.039†</td>
<td>0.033†</td>
<td>0.045†</td>
<td>0.026†</td>
</tr>
<tr>
<td>Tau</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>M</td>
<td>60.91</td>
<td>41.39†</td>
<td>37.45†</td>
<td>37.25†</td>
<td>40.33†</td>
</tr>
<tr>
<td>SD</td>
<td>79.34</td>
<td>53.75†</td>
<td>47.59†</td>
<td>51.87†</td>
<td>44.29†</td>
</tr>
</tbody>
</table>

* Statistically significant effect.
† Significantly different than block 1.
‡ Significantly different than block 2.

Block effects were prevalent for all measures, save the mean within subject SDs of ln(RMSE), $F(4, 24)=0.62, p>.65$. The first block of practice was found to have greater ln(RMSE) than the other four, and the second block differed from the fifth, $F(4, 24)=41.56, p<.0001$. The first block of practice had lower cross correlations than the remaining blocks for both cross correlation, $F(4, 24)=47.90, p<.0001$, and maximum cross correlation, $F(4, 24)=19.41, p<.0001$, as well as greater lags than the other blocks, $F(4, 24)=6.04, p<.0025$. This trend held for the mean within subject SDs of these three measures: cross correlation, $F(4, 24)=18.28, p<.0001$, maximum cross correlation, $F(4, 24)=12.19, p<.0001$, and Tau, $F(4, 24)=17.21, p<.0001$. Thus, with the groups taken together, improvement with practice was evident (see Table 6c).

Practice level by block interactions were used to test the prediction that more practice led to better performance. The relevant data are shown in Figure 13. Such interactions were found for ln(RMSE) and cross correlation, the two overall performance measures. For ln(RMSE), $F(4, 24)=9.11, p<.0001$, a number of significant differences...
were found (see Figure 13A). The LP groups performed in blocks 3, 4, and 5, with less error than in the first block, as well as with less error in block 5 than block 2. The HP groups performed with more error in the first block than for any other, as well as with more error in block 2 than block 5. Comparing the two practice levels, performance was equivalent at for the first block, thereafter the HP groups performed better than the LP groups for each block. Similar effects were found for cross correlation, $F(4, 24)=3.11$, $p<.05$. For the LP groups, the first practice block had a lower cross correlation than the final three blocks, while for the HP groups, the first block differed from all others (see Figure 13B). Performance between the LP and HP groups were differentiable for blocks 2, 3 and 4, but not for the first and fifth. Maximum cross correlation, $F(4, 24)=1.63$, $p>.20$, and Tau, $F(4, 24)=0.27$, $p>.89$, did not yield significant practice level by block interactions (Figure 13C and 13D, respectively).
Figure 13 A. and B. Significant practice level by block interactions. A. Mean ln(RMSE) significant interaction, while mean within subject SDs are virtually the same regardless of practice level. B. Significant mean cross correlation interaction. No effect found for mean within subject SDs.
Figure 13 C. and D. Practice level by block interactions for means and mean within subject SDs of maximum cross correlation (C.) and Tau (D.) were nonsignificant over the five practice blocks used in the analysis.
Figure 14 A. and B. Posttest movement duration by block interactions. Mean and mean within subject SDs over the 5 blocks of practice for A. ln(RMSE) and B. cross correlation.
As is evidenced in Figure 14 A to D there were no significant movement duration by block effects: Mean ln(RMSE), F(8, 48)=1.49, p>.18; cross correlation, F(8, 48)=0.68, p>.70; maximum cross correlation, F(8, 48)=0.86, p>.55; Tau, F(8, 48)=0.52,
p > .83; and mean within subject SDs ln(RMSE), F(8, 48) = 0.50, p > .85; cross correlation, F(8, 48) = 0.65, p > .73; maximum cross correlation, F(8, 48) = 0.85, p > .56; Tau, F(8, 48) = 0.73, p > .66. This indicates that there was no carry over effects of the ten pretest trials to practice performance.

Finally in this examination of the effect of practise on performance, the three way interaction, practice level by posttest movement duration by block, was considered. The crossing of the practice level by posttest movement duration factors yielded the six different groups used in this experiment. These data can be seen in Figures 9 through 12. In no instance was this three way interaction significant. Thus, over the five blocks of practice considered, the six groups did not differ in their performance of the movement at a 2.20 second duration.

The HP groups all displayed improvement over the course of the practice session. Interestingly, though, very little improvement occurred from trial 70 to trial 300. This has interesting implications for the number of trials the LP groups performed, and will be discussed later.

Therefore, there is convincing evidence that all groups improved performance with practise, and that the HP groups demonstrated a decrease in variability with practise. Subjects were able to improve with practise, which is taken here as an indication of learning.

The Pretest: Initial Effect of Movement Duration

Examination of the pretest performance lends an interesting complement to the analyses of the transition from practice to the posttest. These data were submitted to 2 level of practice by 3 posttest condition repeated measures ANOVAs, for both the mean values and the mean within subject SDs. The pretest results, shown in Tables 7a-c, indicate that there were no differences among the groups. Therefore, any differences that are seen in the
posttest are a result of the intervening practice session, as the pretest and posttest conditions were exactly alike.

Table 7a. Pretest results for level of practice.

<table>
<thead>
<tr>
<th></th>
<th>LP</th>
<th>HP</th>
<th>F(1, 36)</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>ln(RMSE)</td>
<td>M 2.141</td>
<td>2.129</td>
<td>0.03</td>
<td>&gt;.87</td>
</tr>
<tr>
<td></td>
<td>SD 0.334</td>
<td>0.298</td>
<td>1.26</td>
<td>&gt;.26</td>
</tr>
<tr>
<td>C.C.</td>
<td>M 0.673</td>
<td>0.710</td>
<td>0.38</td>
<td>&gt;.54</td>
</tr>
<tr>
<td></td>
<td>SD 0.251</td>
<td>0.239</td>
<td>0.06</td>
<td>&gt;.81</td>
</tr>
<tr>
<td>Max. C.C.</td>
<td>M 0.822</td>
<td>0.849</td>
<td>0.72</td>
<td>&gt;.40</td>
</tr>
<tr>
<td></td>
<td>SD 0.146</td>
<td>0.140</td>
<td>0.03</td>
<td>&gt;.87</td>
</tr>
<tr>
<td>Tau (msec.)</td>
<td>M 32.08</td>
<td>67.50</td>
<td>2.05</td>
<td>&gt;.16</td>
</tr>
<tr>
<td></td>
<td>SD 160.23</td>
<td>142.10</td>
<td>0.81</td>
<td>&gt;.37</td>
</tr>
</tbody>
</table>

No level of practice effects were predicted, as the subjects had not yet performed the practice session. None were found.

Table 7b. Pretest results for posttest condition.

<table>
<thead>
<tr>
<th></th>
<th>2.20</th>
<th>2.64</th>
<th>3.30</th>
<th>F(2, 36)</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>ln(RMSE)</td>
<td>M 2.223</td>
<td>2.158</td>
<td>2.024</td>
<td>2.31</td>
<td>&gt;.11</td>
</tr>
<tr>
<td></td>
<td>SD 0.308</td>
<td>0.334</td>
<td>0.305</td>
<td>0.32</td>
<td>&gt;.72</td>
</tr>
<tr>
<td>C.C.</td>
<td>M 0.623</td>
<td>0.680</td>
<td>0.770</td>
<td>2.04</td>
<td>&gt;.14</td>
</tr>
<tr>
<td></td>
<td>SD 0.278</td>
<td>0.274</td>
<td>0.183</td>
<td>1.63</td>
<td>&gt;.20</td>
</tr>
<tr>
<td>Max. C.C.</td>
<td>M 0.815</td>
<td>0.830</td>
<td>0.862</td>
<td>0.76</td>
<td>&gt;.47</td>
</tr>
<tr>
<td></td>
<td>SD 0.170</td>
<td>0.150</td>
<td>0.109</td>
<td>1.22</td>
<td>&gt;.30</td>
</tr>
<tr>
<td>Tau (msec.)</td>
<td>M 57.19</td>
<td>51.24</td>
<td>40.94</td>
<td>0.15</td>
<td>&gt;.86</td>
</tr>
<tr>
<td></td>
<td>SD 163.31</td>
<td>140.69</td>
<td>149.50</td>
<td>0.43</td>
<td>&gt;.65</td>
</tr>
</tbody>
</table>

The results displayed in Table 7b indicate that the duration of the movement was not a factor in its performance, as performance of the movements was statistically indistinguishable. The results of the 2 practice level by 3 posttest movement duration also
indicate that there were no differences in the pretest in the performance of the movement at the three different durations.

Table 7c. Pretest performance and the results of comparative analyses for practice level and movement duration.

<table>
<thead>
<tr>
<th></th>
<th>LP</th>
<th></th>
<th>HP</th>
<th></th>
<th>F(2, 36)</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2.20 2.64 3.30</td>
<td></td>
<td>2.20 2.64 3.30</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ln(RMSE)</td>
<td>M 2.229 2.1778 2.018</td>
<td></td>
<td>2.217 2.138 2.031</td>
<td></td>
<td>0.04</td>
<td>&gt; .96</td>
</tr>
<tr>
<td>SD</td>
<td>0.324 0.358 0.318</td>
<td></td>
<td>0.292 0.309 0.292</td>
<td></td>
<td>0.05</td>
<td>&gt; .95</td>
</tr>
<tr>
<td>C.C.</td>
<td>M 0.605 0.651 0.762</td>
<td></td>
<td>0.641 0.709 0.779</td>
<td></td>
<td>0.04</td>
<td>&gt; .96</td>
</tr>
<tr>
<td>SD</td>
<td>0.269 0.317 0.165</td>
<td></td>
<td>0.286 0.231 0.202</td>
<td></td>
<td>0.63</td>
<td>&gt; .54</td>
</tr>
<tr>
<td>Max. C.C.</td>
<td>M 0.800 0.810 0.856</td>
<td></td>
<td>0.830 0.849 0.868</td>
<td></td>
<td>0.06</td>
<td>&gt; .94</td>
</tr>
<tr>
<td>SD</td>
<td>0.162 0.184 0.092</td>
<td></td>
<td>0.179 0.116 0.126</td>
<td></td>
<td>0.92</td>
<td>&gt; .40</td>
</tr>
<tr>
<td>Tau (msec.)</td>
<td>M 28.05 61.14 7.05</td>
<td></td>
<td>86.34 41.33 74.83</td>
<td></td>
<td>1.26</td>
<td>&gt; .29</td>
</tr>
<tr>
<td>SD</td>
<td>173.90 148.97 157.82</td>
<td></td>
<td>152.72 132.41 141.19</td>
<td></td>
<td>0.01</td>
<td>&gt; .99</td>
</tr>
</tbody>
</table>

Final Practice Block: Effect of the Amount of Practise

Comparisons among the groups at the end of practice provide information regarding the level of movement performance that the groups reached. The prediction that more practise would result in better performance was tested in the block analyses presented in an earlier section. By looking at only the final practice block (10 trials) within these analyses these comparisons can be made.

Practice level by block interactions were examined to investigate this prediction. These data are displayed in Figure 13. The significant effect for ln(RMSE) yielded a significant difference between the HP and LP groups for block 5 of practice. This difference approached significant levels for mean cross correlation (HSD_α=.05=0.0498, actual difference=0.0475). The practice level by block interaction was not significant for mean maximum cross correlation, mean Tau, nor for any of the mean within subject SDs. For mean maximum cross correlation, however, the trend was for the HP groups to perform better over the final ten practice trials than the LP groups (see Figure 13C).
Thus, there is some statistical evidence to confirm the graphic evidence (Figure 13) that more practice led to superior end of practice performance.

**The Transition to the Posttest**

For each measure, a 2 practice level by 3 posttest movement duration by 3 period by 2 block repeated measures ANOVA was performed. The three periods were defined as the end of practice, the beginning of the posttest and the end of the posttest, and there were two blocks of 5 trials within each period. In this manner the effect of the transition from the end of practice to the posttest could be evaluated.

One of the two main predictions of this experiment were evaluated in these analyses. Specificity of motor learning predicts that when transferring to a variation of a practised movement, the ability to perform that movement will be affected by the amount of practise at the original task. Thus, significant practice level by posttest movement duration by period by block effects would indicate just that.

Looking at the practice level by posttest movement duration by period by block interactions, significant effects were found for mean maximum cross correlation, $F(4, 24)=3.06, p<.05$, and mean Tau, $F(4, 24)=3.40, p<.025$, but not for mean ln(RMSE), $F(4, 24)=1.67, p>.19$, mean cross correlation, $F(4, 24)=0.75, p>.56$, nor for the mean within subject SDs of ln(RMSE), $F(4, 24)=1.46, p>.24$, cross correlation, $F(4, 24)=0.67, p>.61$, maximum cross correlation, $F(4, 24)=1.53, p>.22$, or Tau, $F(4, 24)=0.51, p>.72$.

For the mean measures the nonsignificant four way interactions are presented in Figures 15a and 15b while the significant four way interactions are presented in Figures 15c and 15d. For the measure mean maximum cross correlation, the differences of interest are for the LP-2.20 group, which continued to increase their mean maximum cross correlation values from the end of practice to the end of the posttest, with the last 5 posttest trials...
Figure 15a. ln(RMSE) blocked over five trials for the transition period. Note the trend consistent for all groups to suffer a transient increase in ln(RMSE) early in the posttest, especially for the HP-3.30 group. These increases were all nonsignificant.
Figure 15b. The transition period data for the measure cross correlation. The steady improvement of the LP-2.20 group is evident.
Figure 15c. Mean maximum cross correlation data for the transition period. The performance dip for the first block of posttest is evident for the HP-3.30 group, as well as the slight decrease in maximum cross correlation during the second posttest block for the HP-2.64 group.
Figure 15d. Mean Tau results for the transition period. The switch to lead the criterion during the first posttest block by the HP-3.30 group demonstrates the initial difficulty experienced by this group when the movement duration was increased.
having a higher mean value than the last two blocks of practice or the first two blocks of the posttest. Also, the second to last block of the posttest had a higher mean maximum cross correlation value than the second to last practice block and the first posttest block. This improvement of the LP-2.20 group allowed this group to catch up to the LP-2.64 and LP-3.30 groups, which demonstrated no performance differences across the transition period, but performed better than the LP-2.20 group over the last 2 practice blocks and the first 2 posttest blocks. The HP-2.64 group performed with a higher mean maximum cross correlation in the second to last practice block than they did in the second posttest block, and the HP-3.30 group was worse in the first posttest block than in any other block. The HP-3.30 group also had a lower mean maximum cross correlation over the first 5 posttest trials than the HP-2.20 or HP-2.64 groups.

For the measure mean Tau, no significant differences in performance were found within or among the three LP groups. The HP-2.20 and HP-2.64 groups demonstrated no within group differences across the transition period, either. The HP-3.30 group, however, showed a marked change in the ability to time the movement in the first posttest block compared to the final block of practice. In addition, the HP-3.30 group differed in the first posttest block from the performance of the HP-2.64 group over this same block.

Therefore, evidence for the specificity hypothesis was found. For mean maximum cross correlation, the lack of change within a group across this transition period for the LP-2.64 and LP-3.30 groups indicate that the sensorimotor representations that were being used to control the movement in the practice were flexible, allowing the use of the same sensorimotor representation for the longer duration movement. Also, as expected, the HP-2.20 group showed no performance changes as a result of the transition (as there was no change in movement duration), while the HP-2.64 and HP-3.30 groups did suffer performance decrements early in the posttest. For mean Tau, similar evidence for
specificity was found. The three LP, the HP-2.20, and HP-2.64 groups showed no within group performance changes across the transition period. The HP-3.30 groups did suffer a large change in the ability to time the movement sequence, but only very early in the posttest session. Thus, the specificity effect was present, but apparently very short-lived.

To investigate the second main prediction of this experiment, the prediction that a generalization gradient would appear as the duration of the movement in the posttest became increasingly larger than the practised movement duration, the absolute change in the mean and mean within subject SD for each performance measure was calculated for each subject based on the mean of the last 5 practice trials and the mean of the initial 5 posttest trials. These difference scores were submitted to 2 practice level by 3 posttest movement duration repeated measures ANOVAs. The prediction was that the largest change in performance as a result of the transition to the posttest would be seen in the 3.30 groups in general, or more specifically in the HP-3.30 group. The least change would occur in the 2.20 groups, with intermediate change occurring for the 2.64 groups. Thus, the analyses of interest involve the main effect for posttest movement duration and the practice level by posttest movement duration interaction. These predictions were based on the stimulus generalization notion.

For the main effect of posttest movement duration, displayed in Figure 16, non-significant results were obtained for mean ln(RMSE), $F(2, 36)=0.91, p>.41$, and mean cross correlation, $F(2, 36)=1.08, p>.35$, although the trend was in the predicted direction in both instances. Mean maximum cross correlation yielded a main effect for the difference between the end of practice and the posttest, $F(2, 36)=7.67, p<.0025$. Post hoc analyses indicated that the groups performing the movement with a duration of 3.30 sec. had a larger change (decrease) in maximum cross correlation than either of the two other sets of groups, who performed the 2.20 or 2.64 sec. movement. Similarly, the mean temporal measure,
Tau, indicated that the 3.30 groups suffered a larger change in timing ability in the transition than the other groups, \( F(2, 36)=8.15, p<.0025 \).

![Graph A](image1.png)

![Graph B](image2.png)

![Graph C](image3.png)

![Graph D](image4.png)

Figure 16. Absolute difference scores (the mean of last 5 practice trials minus the mean of first 5 posttest trial for each subject) for the trials immediately surrounding the transition. A. \( \text{ln(RMSE)} \) and B. cross correlation demonstrate the predicted gradient, but did not reach significance. C. maximum cross correlation and D. Tau provided significant differences between the 3.30 sec. movement duration and the other duration.

The interaction between the level of practice and the posttest movement duration yielded nonsignificant results for mean \( \text{ln(RMSE)} \), \( F(2, 36)=0.93, p>.40 \), mean cross correlation, \( F(2, 36)=0.71, p>.50 \), and mean Tau, \( F(2, 36)=2.47, p>.09 \), although this
last nearly reached conventional levels of significance. A significant interaction was obtained for mean maximum cross correlation, $F(2, 36)=4.90, p<.025$. Post hoc analyses indicated that this difference was a result of the HP-3.30 group undergoing a larger change in transition than any other group. These data are presented in Table 8.

Table 8. Absolute difference between the mean of the last five practice trials and mean of the first 5 posttest trials for the practice level by posttest movement duration interaction.

<table>
<thead>
<tr>
<th></th>
<th>LP</th>
<th></th>
<th></th>
<th>HP</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2.20</td>
<td>2.64</td>
<td>3.30</td>
<td>2.20</td>
<td>2.64</td>
<td>3.30</td>
</tr>
<tr>
<td>ln(RMSE)</td>
<td>-0.052</td>
<td>-0.131</td>
<td>-0.098</td>
<td>-0.132</td>
<td>-0.111</td>
<td>-0.300</td>
</tr>
<tr>
<td>C.C.</td>
<td>0.011</td>
<td>0.029</td>
<td>0.028</td>
<td>0.020</td>
<td>0.010</td>
<td>0.050</td>
</tr>
<tr>
<td>Max. C.C.*</td>
<td>0.012†</td>
<td>0.010†</td>
<td>0.016†</td>
<td>0.008†</td>
<td>0.005†</td>
<td>0.053</td>
</tr>
<tr>
<td>Tau (msec)</td>
<td>16.71</td>
<td>4.57</td>
<td>33.14</td>
<td>-8.95</td>
<td>-23.57</td>
<td>64.42</td>
</tr>
</tbody>
</table>

* Statistically significant effect.
† Significantly different than HP-3.30.

The difference between the mean within subject SDs over the final 5 practice trials and the first 5 posttest trials yielded no duration effects for ln(RMSE), $F(2, 36)=1.44, p>.25$, cross correlation, $F(2, 36)=0.19, p>.82$, or Tau, $F(2, 36)=1.94, p>.15$. A significant posttest movement duration effect was found for the mean difference in the within subject SDs for maximum cross correlation, $F(2, 36)=9.07, p<.001$, which was found to be the result of the 3.30 groups experiencing a greater increase in mean within subject SD than the other groups. Similarly, the interaction was significant only for the mean difference of the mean within subject SD of maximum cross correlation, $F(2, 36)=4.50, p<.025$, which was the result of the HP-3.30 groups having a larger difference than any other group. Nonsignificant interactions were obtained for ln(RMSE), $F(2, 36)=1.63, p>.20$, cross correlation, $F(2, 36)=0.84, p>.44$, and Tau, $F(2, 36)=0.62, p>.54$. These data are presented in Table 9.
Table 9. The mean difference between the mean within subject SD for last five practice trials and the first 5 posttest trials. The data are given for the main effect of posttest movement duration (top) and for the interaction between posttest movement duration and level of practice (bottom).

<table>
<thead>
<tr>
<th></th>
<th>2.20</th>
<th>2.64</th>
<th>3.30</th>
</tr>
</thead>
<tbody>
<tr>
<td>ln(RMSE)</td>
<td>-0.019</td>
<td>0.010</td>
<td>-0.074</td>
</tr>
<tr>
<td>C.C.</td>
<td>-0.018</td>
<td>-0.017</td>
<td>-0.028</td>
</tr>
<tr>
<td>Max. C.C.*</td>
<td>-0.006</td>
<td>-0.001</td>
<td>-0.029</td>
</tr>
<tr>
<td>Tau (msec)</td>
<td>-13.90</td>
<td>-55.58</td>
<td>-66.12</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>2.20</th>
<th>2.64</th>
<th>3.30</th>
</tr>
</thead>
<tbody>
<tr>
<td>ln(RMSE)</td>
<td>0.033</td>
<td>-0.019</td>
<td>-0.096</td>
</tr>
<tr>
<td>C.C.</td>
<td>-0.015</td>
<td>-0.022</td>
<td>-0.009</td>
</tr>
<tr>
<td>Max. C.C.*</td>
<td>-0.005†</td>
<td>-0.002†</td>
<td>-0.011†</td>
</tr>
<tr>
<td>Tau (msec)</td>
<td>-17.85</td>
<td>113.23</td>
<td>-66.24</td>
</tr>
</tbody>
</table>

* Statistically significant effect.
† Significantly different than HP-3.30.

Thus it appears that a generalization gradient effect may have resulted when the movement durations in the posttest were increased relative to the practised movement duration. However, where this trend appears the most clearly graphically, the results were not statistically reliable (see Figure 16A and B). In any case, the statistically significant effects indicate that transferring to a much different movement duration (from 2.20 sec. to 3.30 sec.) a larger performance change was seen than when remaining at the same movement duration or transferring to a less dissimilar movement duration (from 2.20 sec. to 2.64 sec.).

**Discussion**

The purpose of this second experiment was to extend the specificity hypothesis from the sensory to the motor output realm. In contrast to Schema theory, it was predicted that the more practise one has at a movement, the more difficult it would be to scale the duration of the movement. In addition, this difficulty would be graded according to the
extent to which the new movement duration was dissimilar to the movement duration practised.

After beginning the experiment with equivalent ability, the subjects in each group demonstrated improvement over the course of practice, indicating that subjects were learning the movement. Taking the final 10 practice trials as indicative of best performance during practice, it was confirmed that having 300 practise trials led to superior performance than having a mere 50 practise trials.

The main point of interest in this experiment was what performance changes occurred when the subjects transferred to the posttest movement duration, which was the same or longer than that originally practised. Predictions were made for within-group effects of the transition to the posttest. For the LP-2.20 group it was predicted that improvements would continue to occur, as in a sense practise was just being continued, and for the HP-2.20 it was expected that no changes in performance would occur. For these control groups, these predictions was largely upheld. However, it appears that the LP-2.20 group's improvement during the posttest merely allowed them to 'catch up' to the performance levels of the LP-2.64 and LP-3.30. For the other two LP groups, LP-2.64 and LP-3.30, it was predicted that performance would not be degraded in the posttest relative to the end of practice. These predictions, too, were upheld.

The two remaining groups, HP-2.64 and HP-3.30, were expected to suffer performance decrements in the posttest relative to the end of practice. The HP-2.64 group showed a decrease in the ability to perform the spatial portion of the movement, with a decrease in the maximum cross correlation occurring in the second block of the posttest. In comparison, the HP-3.30 group demonstrated more wide-ranging performance deficits in the posttest. The HP-3.30 group, performing a movement duration in the posttest that was most unlike that which was practised (relative to the other HP groups), suffered large performance decrements very early in the posttest, displaying a marked inability to adjust to
the proper timing of the movement. That is, over the initial 5 trials of the posttest this group showed a tendency to perform the movement far more quickly than they had previously. In addition, the performance change of the HP-3.30 group was reflected in the spatial measure of performance, as this group produced a lower mean maximum cross correlation over the first 5 posttest trials than for any other 5 trial block in the transition period.

Thus, the results of the present experiment are of interest with respect to the specificity hypothesis. While there was some evidence for the specificity of motor learning hypothesis, in that the inability to transfer to a novel version of the practised task successfully was apparent for the groups with the most practise at the original movement (HP-2.65 and HP-3.30), this performance disruption was relatively short-lived. If, as hypothesized here, the transfer to a novel variations of a practised movement causes a reorganization of the connection between components within a sensorimotor representation, the time course of this reorganization occurred rapidly within the confines of this experimental protocol.

Previously, the depressed performance in the posttest that was seen as evidence for the specificity hypothesis typically had a longer lasting effect than that seen here. Proteau et al. (1987: Figure 5) displayed evidence that this reorganization occurs for at least 20 trials; Proteau et al. (1992: Figure 4) showed evidence that this period lasts at least 40 trials; and Adams et al. (1972: Figure 1) showed this period to last for at least 50 trials. Therefore it is important to try to understand the differences between these experiments, to help explain these results. Proteau and colleagues (1987; 1992) used an aiming task in their studies. Three items are of importance for the current discussion. First, pointing is not a skill that required the subjects to learn. The fact that improvement was seen was probably a result of subjects becoming familiar with the exact conditions used in the experiment. The present study used a more complex and longer duration movement than
these previous studies that required subjects to learn the temporal and spatial characteristics of the movement. The second is that the error resolution is very high for manual aiming studies. For example, differences in temporal errors of less than 3 msec. in the transition from the end of practice to posttest were found to be significant. The low variability that must be associated with such small yet significant differences is possible to obtain with an aiming task, yet were not evident in the present experiment. Even after 300 trials there was a fair amount of trial to trial variability. This may be because we are seldom called upon to learn a movement that must be performed exactly the same way every time. When we do, however, as with a consistent golf stroke, many thousands of practise trials are required.

Which leads to the final item, the amount of practise. A possible reason that the sustained posttest performance decrement was not seen in this experiment (nor in experiment 1) may be the relatively few practise trials used. It is possible that performing 1000 or more trials in the HP conditions would have resulted in a more lasting decrease in performance for the HP-2.64 and HP-3.30 groups in the posttest. However, 1000 trials would have taken approximately 6 hours to perform. Thus, the experiment would have had to be performed over the course of several days. This was not done as it was of some concern what intervening hours, including sleep (Wilson & McNaughton, 1994; Karni et al., 1994), would do to performance and to the internal sensorimotor representation. However, for the sake of testing the specificity hypothesis, all that is truly required is a relative difference in the number of practise trials that yields a relative performance difference in accordance with the predictions of the hypothesis. In this context the present experiments still successfully test the hypothesis.

Another issue with regard to the number of practise trials has to do with the LP groups. In experiment 2, all effects due to practise for the HP groups were because the first ten blocks differed from all others. This means, then, that trials 71-80 did not differ on average from trials 291-300. Thus, floor and ceiling effects (performance plateaus)
were reached after approximately 70 trials. Thus the LP groups had almost reached that performance plateau, which may account for the paucity of evidence (in both experiments) that more practise led to superior end of practice performance.

A final prediction investigated in the present experiment was that of a graded effect in the posttest based on the similarity of posttest movement duration to the practised movement duration. The evidence for this was present, but minimal. The evidence for the gradient was unclear as the gradient appeared most obviously for differences in mean \( \ln(\text{RMSE}) \) and mean cross correlation, but these effects were not found to be statistically reliable. However, the differences for mean maximum cross correlation and mean Tau provided evidence that the groups performing the 3.30 second movement, but especially the HP-3.30 group, experienced larger performance changes than the other groups. Since the movement was slowed down in the posttest, it may have been easier for subjects to perform the posttest movement, such that this generalization process was masked.

Hedges, Dickinson, and Modigliani (1983) demonstrated this effect in the production of linear movements, and suggested that transfer to novel variations of learned movements may be attributed to this generalization process. This explanation fits into the specificity of the sensorimotor representation framework, as more reorganizing of the sensorimotor representation would be required the more different the variant of the learned movement was. In conclusion, limited but promising evidence of generalization was found in the experiment.

This experiment may have benefitted from the inclusion of control groups for the 2.64 and 3.30 second posttest movement durations. That is, groups that practised and were tested performing the longer movement durations may have allowed more precise characterization of the effect on the HP-2.64 and HP-3.30 groups in the posttest. However, the main interest of this study was to investigate the differential within group effects on the LP and HP groups of transferring to unpracticed movement durations. In
this the experiment was successful, although future work or replications of this work should include the complete array of control groups.
GENERAL DISCUSSION

These investigations into the specificity of motor learning hypothesis were important for three reasons. First, in the present two studies a more complex movement was used than in the previous specificity investigations, in which aiming movements were employed in studies of motor learning. Second, the hypothesis was further developed by manipulating the motor output while maintaining the sensory information. All previous studies manipulated the sensory (especially visual) information in the practice relative to the transfer tests. Finally, these results taken with the previous findings in the literature support the specificity of motor learning hypothesis as it has been proposed here, and provide a framework or model for considering the processes of human motor learning.

The next three sections are devoted to discussions of the body of support for the specificity of motor learning hypothesis as outlined here, the implications of these findings on the relation between the practice and the test situations and on the evaluation of learning and the evaluation of the model of motor learning that arises from the specificity of motor learning hypothesis.

Support for the Specificity of Motor Learning Hypothesis

The present experiments provide further support for the specificity of motor learning hypothesis. Again, the hypothesis, as presented in this thesis, states that the learning of a closed movement involves the construction of a sensorimotor representation of the movement within the C.N.S. over practise trials that is based on, and specific to, the conditions that exist during practise. Experiment 1 provided evidence that for a movement requiring spatial and temporal accuracy, novel sensory information introduced after relatively extensive practise caused performance to deteriorate. Then, in experiment 2, similar performance decrements were seen when the duration of a well practised movement

90
was increased. In both cases, these performance deterioration effects were not found in groups that had experienced less practice.

The predictions and results of both experiments were in contrast to the predictions of Schema theory. Schmidt's (1975) theory can be dismissed as an explanatory theory of the present set of results, as Schema theory predicts a decrease in the contribution of the sensory information used in the planning and control of movements as learning occurs. Schema theory is not alone in this prediction of a progression from closed-loop to open-loop control as a movement is learned. The classic stages of motor learning as presented by Fitts and Posner (1967) are based upon this progression. The present results indicate that the maintenance of the sensory information available is important to the successful performance of a movement.

In addition, Schema theory assumes that there are a number of invariant features within a generalized motor program. An overall duration parameter is reported to be one of these invariants. Work by Viviani and Terzuolo (1980) and Carter and Shapiro (1984), for example, has been used as evidence supporting this parameterizable overall duration parameter. This work has been criticized previously for other reasons (see Gentner, 1987), but the results of experiment 2 speak against the existence of an overall duration parameter.

Schema theory was not the only alternative to the specificity of motor learning hypothesis that was considered. As previously mentioned, Fitts and Posner's (1967) description of the stages of learning is based on the diminishing afferent contribution to the planning and control of movement. Obviously no evidence was found here for a strong version of this position. Also, MacKay's (1982) associationist theory, while providing mechanisms to account for positive and negative transfer that would result in predictions that were similar to those of the specificity hypothesis, can also be discounted since little evidence for the scalability of the duration of a movement was found. Transfer-appropriate processing is the alternative theory most like the specificity hypothesis. According to the
transfer-appropriate processing idea, in the present experiments the ability to perform the
movement with the visual feedback (experiment 1) or at a different movement duration
(experiment 2) would be related to the similarity of the processing requirements of the
practised and novel variations of the movement. This hypothesis fails to account for the
differential effect of transfer of the well practised and little practised groups that is the
definitive result in studies finding support for the specificity of motor learning hypothesis.

Evidence has accumulated for a number of decades for the specificity of motor
learning hypothesis, after its beginnings in the work of Henry (1968). The original work
focused on the specificity of skilled motor performance, finding, for example, differential
performance on two apparently highly related tasks requiring balance (Bachman, 1961).
Similarly, subjects that practised a lateral balancing task did not gain any benefits of that
practise when performing an anterior-posterior balancing task (Walsh, 1973). Results
somewhat similar to the present thesis were found when boys from grades 5 and 6 were
trained to hit a target with a ball in four different ways: a tennis volley, a soccer kick, a
volleyball volley, and a soccer punt (Lemcke, 1970). Results indicated specificity in the
performance of these gross motor tasks, but that the specificity effects were short-lived and
existed in the presence of positive transfer. Such was the case in experiments 1 and 2 of
the present work, as the decreases in performance abilities in the early posttest periods
never decreased below initial (pretest or the first block of practice) levels. Thus, positive
transfer was experienced by the subjects in all cases. The only true case of negative
transfer seen in the specificity literature was found by Proteau et al. (1992).

Karni et al. (1995) report finding evidence of specificity of motor learning at the
cortical level. Using rapid sequences of finger movements as the task, the practised task
yielded larger localized responses than a different finger sequencing task made up of the
same elements, as measured by magnetic resonance imaging of the local blood oxygenation
levels. Not only did they find support for the specificity of motor learning hypothesis at
this completely different level of analysis (cortical vs. behavioural), they also posited a similar notion of the representation that is constructed with learning. More anatomical evidence for specificity was found by Pascual-Leone and Torres (1993). Using the measurement of evoked potentials and transcranial magnetic stimulation from blind (Braille reader) and sighted subjects while they received tactile inputs to their fingertips, it was shown that cortical sensorimotor representations of the reading finger of the blind subjects were differentially expanded compared to non-reading fingers and sighted subjects. Thus, through many hours of practise at reading Braille, the sensorimotor representation of the one, reading, fingertip was modified at a neural level. Thus, learning is not only specific, but results in changes at the cortical level.

Additional evidence for the specificity of motor learning hypothesis was found in a study that manipulated the auditory feedback during a speech production task (Pick, Siegel, & Garber, 1982). During speech, the feedback of the subject's own voice was either amplified or attenuated, which tends to elicit a lowering in the speech volume or an increase in the speech volume, respectively. The results indicated that adults were more affected by the manipulations than were 3 and 4 year olds. This was contrary to their hypothesis that auditory feedback would become unnecessary, and thus easy to ignore, for the adults, who had more practise speaking. However, the results fit with the idea of specificity: The practise that the adults had speaking occurred with normal auditory feedback. When that normal auditory feedback was altered, performance was affected.

In contrast, a completely different study found no support for the specificity hypothesis. Bennet and Davids (1995) used the powerlift squat as the movement, and used an expert-novice paradigm. Their results indicated that the experts were not affected by the visual manipulations, while the novices performed better when they were provided vision. While raising the important question of the importance versus the necessity of vision to the performance of the task, and its bearing on research into specificity, they also indicate that
the experts they used did not have exclusive practise at any one level of the visual manipulation, but had more experience at all levels of the visual manipulation compared to the novices, who almost strictly practised under one visual condition. Thus, the experts' experience at the, for example, no vision condition may have been responsible for these results, and not their relatively high level of practice at the full vision condition.

Therefore not all the research into the specificity hypothesis produced positive results. However, over the past ten years a body of support has been growing in the literature. The two experiments reported here expand the boundaries of the sphere of research into the specificity hypothesis.

**Implications of the Hypothesis**

The specificity of motor learning hypothesis raises important theoretical and practical issues. The paradigms used in the study of motor learning must be re-evaluated in the light of specificity. Also, training techniques and environments should be implemented with due consideration of the specificity of motor learning hypothesis.

**Re-evaluation of the Motor Learning Paradigms**

Research on motor learning, the present thesis experiments included, tends to employ some variation on a pretest-posttest paradigm then attributes any differences in the posttest performance relative to the pretest as a result of the intervening practice session. Often, two (or more) practised variations of the goal movement, or different practise schedules using the goal movement, are compared as to their benefits on subsequent performance of the goal movement. For example, Goode and Magill (1986) trained novices three badminton serves using one of three different training schedules, blocked, serial, or random practise. After the training session, ability to serve and the usefulness of the different training schedules were evaluated in a retention test (~24 hours after the final training session). This retention test was comprised of the three serves that had been practised being performed randomly. Is it any surprise, based on the results of the present
experiments, that the group that practised the serves under a random schedule performed
the best in the retention test? And that the blocked group performed the worst? It is
difficult to attribute this retention test superiority of the random group strictly to the random
practise schedule when the experimental paradigm used to evaluate the schedules worked in
favour of those that had the random practise. This difficulty in the experimental paradigms
used and the conclusions drawn from them need to be considered with knowledge of the
specificity of motor learning hypothesis.

Two prominent authors of texts on motor learning, Magill (1989) and Schmidt
(1988), both suggest the use of transfer and retention tests to evaluate learning properly, as
direct observations can sometimes also lead to incorrect conclusions. Factors such as
motivation and fatigue have been fingered as culprits, as they can often make performance
appear poor, when in actuality the degree of learning and the ability to perform the
movement are high. Schmidt (1988) defines transfer designs as an "experimental design
for measuring learning effects, in which all treatment groups are transferred to a common
level of the independent variable" (p. 376). No recommendations, or even words of
cautions, are offered for choosing this "common level of the independent variable" for the
transfer test. It is difficult for the experimenter to know intuitively if the condition used in
the transfer test is equally similar to all the different conditions used in the practice
sessions. Thus learning studies are hampered by the current experimental paradigms.

Implications for Training and Simulations

When developing training procedures and environments, the principles of
specificity must be considered. The important consideration is the goal of the training.
That is, practice sessions and schedules must be created to allow not just the facilitation of
the learning of the movement, but also the high similarity between the practice and goal
situations. For example, in the badminton serve experiment (Goode & Magill, 1986) a
game situation would probably require serves to be randomly performed, to keep the
opponent from anticipating the serve. Then it is important that the practice facilitate the ability to perform the different serves in a random order. However, if necessary, it may be beneficial early in the practice session to practise the serves in a blocked manner to familiarize the learner with the unique characteristics of each serve. Thus combination training sessions, accommodating the specificity effect but not ignoring the extensive training literature, should be used.

Much research is currently being invested in the production of artificial environments, for use in simulation and entertainment. Knowledge of the specificity of motor learning hypothesis needs to be injected into such research. For example, imagine learning to fly an airplane in a simulator which has a black and white, 2-D display, with display-related time lags of 500 msec. If after extensive practise one were to become a perfect pilot in this artificial environment, how much of this newly acquired skill and ability would transfer to the real world, which is in colour, is 3-D, and has no display-related time lags? Thus simulator training must be evaluated on a cost-benefit basis. Does the time spent in the simulator have an immediate effect on flying in the real world? If that affect is positive, then the simulator is useful. However, if simulator practise is detrimental, how long does that detriment last? If it is transient, and eventually results in performance benefits, then, again, the simulator is useful (but less so than the first example). If the detriments are not transient, and do more harm than good, the simulated environment should be changed to facilitate transfer to the real world. A recent experiment lends support to this argument. In a simulated environment that was used in the training of a pick-and-place task, subjects were found to have learned performance characteristics of the task that were specific to the virtual version of the task, and did not transfer to the real world version of the task (Kozak et al., 1993). This, of course, is all a result of the specificity with which humans learn movements.
Evaluation of the Model of Motor Learning

As presented here, the specificity of motor learning hypothesis is set on a framework of connectionism. It is of interest to evaluate the hypothesis and the accompanying model of learning that it suggests. This can be accomplished by considering the evidence suggesting that the brain may work like a connectionist network, and the ability of this model of learning to account for other motor learning phenomena.

Neural Connectionism

Churchland (1989) questioned the faithfulness with which artificial neural networks depict the brain's structure and function. While the brain does have a massively parallel construction, with different synaptic weights for various connections, just like in artificial networks, the details of brain function make apparent the inadequacies of such models. First, unlike the models, not every brain neuron projects to every other neuron. Also, for a given neuron, it appears that all of the terminals are uniformly inhibitory or excitatory, again, unlike the artificial networks. Finally, for the purpose of these discussions, artificial networks tend to use back-propagation error correction mechanisms that do not occur in the brain. Despite these, and other, failings, artificial neural networks are merely models of the brain, simplifications that account for some of the behaviours of the brain. Such brain-style computation (Rumelhart, 1989), while not a perfect representation of brain function, is a step closer to brain function than the serial-computer analogy that has persisted for decades in the motor learning literature.

To attest to the usefulness of the connectionist model, neural networks have been used successfully by researchers to model insect walking (Dean, 1990), learn to control a two-segment limb in a step and smooth pursuit tracking tasks (Kalveram, 1993), learn to control a robotic manipulator (Kawato, Furukawa, & Suzuki, 1987), and replicate the contextual interference effect (Horak, 1992). Finally, in recent research testing two opposing hypotheses regarding the structure of the internal representation used to control
movements, Imamizu, Uno, and Kawato (1995) found evidence for a third representation, a connectionist representation. Thus, while it is only a simplification of the human brain, connectionism is a useful tool for motor learning researchers.

**How Well Does this Model of Learning Account for other Motor Learning Phenomena?**

Again, the specificity of motor learning hypothesis, as outlined in the present thesis, relies on the idea of the construction of sensorimotor representations, which are speculated here to be connectionist networks. The hypothesis itself suggests a model of motor learning. Four motor learning phenomena are re-considered from the standpoint of the model.

The "novelty problem" of Adams' closed loop theory of motor learning prompted Schmidt (1975) to develop Schema theory and the notion of generalized motor programs. Connectionist systems have as one of their inherent properties the ability to generalize, and thus produce novel responses (Rumelhart, 1989). Thus, in this case, sensorimotor representations can account for this property of Schemata.

Two similar phenomena, the contextual interference effect and the benefits of variable practise can also be explained using a connectionist model. Typical contextual interference studies have three conditions, blocked practise, serial practise, and random practise. If learning is the modification of the weights of neural connections, then random (and to an extent, serial) practise results in high trial to trial variability, and consequently large changes to the connections' weights. This will perturb the system, and prevent it from settling into a less than optimal configuration, pushing it towards a global configuration capable of accounting for all the learned material. With blocked practise, the network quickly settles into a state to solve the one problem that it is practising. When the next block of practice starts the system is perturbed out of that local configuration and settles into a new local configuration, and so forth, never being forced towards the global.
Thus, in the transfer tests of such studies, the random-trained networks are better able to generalize than the blocked-trained networks, resulting in the contextual interference effect. In this same manner, variability of practise (Schmidt, 1975) would also lead to a better trained network that would be better able to generalize.

Internal mental imagery can be defined as imagining the somatosensory outcomes that would accompany the actual performance of the goal movement, and has been shown to have beneficial effects on motor performance (Magill, 1989). Jeannerod (1995) presents a summary of a number of studies that found physiological events that correlated to mental imagery. Increases in EMG over resting levels in the limb involved in the imagined movements, as well as small movements during imagery sessions have been reported. Neural activity has also been found, such as increased spinal excitability, activation of the supplementary motor area, and contralateral sensory and motor corticies. Thus imagery has an effect at both the sensory and motor levels. Thus, sensorimotor representations that are hypothesized here as the networks involved in the control of learned movements can be constructed or modified based on the afferent and efferent consequences of imagery. Obviously imagery is not as beneficial as actually performing the movement (Magill, 1989), but its benefits fit into the idea of connectionist sensorimotor representations.

Finally, stimulus generalization, one of the predictions of experiment 2, can also be described using connectionist networks. Briefly, response probability (or response correctness) decrease as the stimulus (movement) becomes increasingly unlike the practised stimulus (movement) (Lieberman, 1990). This generalization gradient can be accounted for by the properties of connectionist networks. Networks are only as good at producing generalized responses as their training set represents the full panoply of possible stimulus-response sets (Churchland, 1989). The ability of a network to generalize decreases as the required responses fall further outside the training set (Ivens, 1994). Thus, if a network was trained to respond to the equivalent of a 580 nm. light (yellow), response probability
would decrease as the wavelength was increased (towards an orange or red light) or decreased (towards a green or blue light). This is what is observed as the stimulus generalization effect.

In the second experiment, limited evidence was found for the predicted stimulus gradient. This failed extension of the findings of Dickinson and Hedges (1986) may have been because of the way the present tasks were modified. Using slower movements as test of generalizability may have failed to produce the effect clearly because movement sequence may have been easier to produce at the slower (posttest) rates than at the practised rate. There was, however, sufficient evidence to suggest that the effect may be reproducible in such a task. One option may be to vary the shape of the required movement sequence systematically. At any rate, the hint of the effect observed in experiment two can be explained by the connectionism-based sensorimotor representation, as can the ability to generalize to novel movements, the contextual interference effect, the hypothesized benefits of variability in practise, and mental imagery.

Conclusions

In conclusion, the present two experiments did produce evidence for the specificity of motor learning hypothesis. This effect, however, was found to be very short in duration. In addition, even though changing either the sensory or motor aspects of the movement after much practise produced the tell-tale performance decrements, positive transfer as a result of the practice session was in evidence. Thus, the story of specificity is not a simple one, and more studies should be undertaken to further characterize the specificity of motor learning. In addition, promising though limited, evidence was gathered that suggests that movements of this type can be used to demonstrate a generalization gradient in keeping with previous stimulus generalization findings.

More research is also required to elucidate the relationship between the amount of practise and the time course of the reorganization of the sensorimotor representation that
occurs when a novel variation of a practised movement is introduced. Finally, further considerations into the usefulness of the sensorimotor representation model of learning are warranted.
REFERENCES


