LEARNING A NEW BIMANUAL COORDINATION PATTERN

RECIPROCAL INFLUENCE OF LEARNING A NEW BIMANUAL COORDINATION PATTERN AND PERFORMING EXISTING COORDINATION PATTERNS

By

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A Thesis
Submitted to the School of Graduate Studies
in Partial Fulfillment of the Requirements
for the Degree
Master of Science

McMaster University

MASTER OF SCIENCE (1995) McMASTER UNIVERSITY
(Human Biodynamics) Hamilton, Ontario

TITLE: Reciprocal Influence of Learning a New Bimanual Coordination Pattern and Performing Existing Coordination Patterns

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NUMBER OF PAGES: x, 121

Abstract

Popular theories of motor learning (e.g., Adams, 1971; Schmidt, 1975) rely heavily on formation of new skills through refinements of pre-existing ones. Dynamic Pattern Theory has the advantage of being able to assess initial individual differences on the required task so that the subject becomes the important unit of measure. The general purpose was to identify the reciprocal influence of intrinsic patterns and learning a new pattern.

In two experiments subjects were required to practice a rhythmic bimanual coordination task of the forearms using linear sliding devices. In the first experiment, 7 subjects practiced a 90° relative phase pattern for 45, 15 s trials on each of 6 practice days. In-phase and anti-phase trials were performed pre- and post-practice. Subjects were provided terminal feedback with a Lissajou figure after each practice trial and augmented feedback was provided after every 5th practice trial. Mean constant error (CE) for individual subject data and absolute CE (| CE |) for group data were used as measures of accuracy. Standard deviation of relative phase was used as a measure of stability (VE). Subjects were able to learn the 90° pattern and performance plateaued by the fourth practice day. Neither intrinsic pattern showed any destabilization, although a temporary decrease in accuracy (CE) within days was found. The four week retention test revealed no change for any pattern.

Experiment 2 compared two groups practicing either 45° or 135° relative phase. It was predicted that the 135° relative phase pattern would be

easier to learn because of the reduced competition from the less stable 180° intrinsic pattern. The procedure was similar to Experiment 1 except that subjects practiced for only four days. Performance of the practiced patterns was never as accurate as 0° and 180° but variability of performance was not different for both practiced and intrinsic patterns by Day 4. There was no difference in either accuracy or stability between the two groups on the practiced patterns. As in Experiment 1, there was no change from the last day of practice to the four week retention test.

Individual subject data revealed numerous different paths to learning the required pattern. Constant error and VE values for intrinsic patterns were not particularly good predictors of ability to learn the practiced pattern. Additionally, a low VE was not indicative of a low CE or vice-versa when practicing the required pattern.

The results from both experiments show that early in learning, competition biases performance away from the intrinsic attractors. Later in practice, subjects stabilize their performance of the new pattern and the intrinsic patterns do not destabilize. Differences in performance of the required pattern may have depended, not only on dynamic principles, but also on motivation, handedness, and conceptualization of the task.

Acknowledgements

Every rower knows that the key to a successful race is being prepared. There are many people I have to thank for helping me become well prepared over the past two-and-a-half years.

Of course, I would never have gotten this opportunity if it wasn't for my parents. All the praise and thanks in the world would not be enough. Having begun the training, though, Marion and Arthur were always there to help give me the right perspective.

I have had three coaches. Geri Van Gyn was the first to get me excited about the wonderful topic of motor learning and continues to provide invaluable support. Digby Elliott took over when I relocated to Hamilton. He was the first to demonstrate to me how elegant (and fun) experimentation could be. My most important coach has been Timothy Lee. I have enjoyed very much learning from and being challenged by Tim. I will always remember how important Tim was in making an exciting training plan and helping me revise it when necessary.

Just as important have been my training group. Most times, they were a positive influence to keep me on schedule but sometimes we temporarily lost sight of the goal and got a bit behind. To Mo, Marty, and Katie, you have helped me reach my goals more than you could know. For Bill, a special thanks for keeping the training so entertaining. To Kerry and Kevin, I thank you for giving me unexpected perspectives on school, training, and life. There are many others who joined the team later but remain just as special - again, thank-you.

All good teams need a manager. I could always count on Mary Cleland to know what to do, who to call, or where to go when I needed something.

To complete a good team or training group there are individuals who create there own special roles and become a positive influence. Brian Maraj has been just such a person since my arrival. My other committee members, Janet Starkes and Laurie Swanson have been equally as influential.

And for those who told me, "You can always go back to school but this might be your only time to row," a special thank-you for your patience and support. Finally, I would just like to thank everyone for "looking out for me" and I hope to repay you all in the best way I can think of - winning an Olympic medal!

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Introduction

Present theories of learning rely heavily on explaining motor learning through the strengthening of pre-existing representations of the movement. Adams (1971) used the concept of a memory trace that initiated the action. Feedback was then used to compare the ongoing movement control to the perceptual trace. Schmidt's Schema Theory (1975) relied less on feedback with generalized motor programs. A motor program could initiate a movement that would either run off without feedback or be adjusted based on feedback if the movement was long enough. In both theories, however, formation of the initial movement patterns (memory trace or motor program) was not discussed. It remained unaddressed whether these initial movement patterns originated from innate motor tendencies that were then adapted for the specific task or if they were somehow initiated from other beginnings.

Associated with the problem of determining how a movement pattern is first created is the concept of assessing individual differences before learning begins. Most experimental designs account for individual differences by having subjects learn a novel task In this way, since none of the subjects have previous experience with the task, individual differences are equated (in theory). As noted by some (e.g., Newell, 1985), it is often parameters of a previously learned skill that are practiced and not an entirely new movement pattern. Presumably, pre-existing motor skills may affect the learning of new ones even if the pattern is novel.

Group data are often used to demonstrate learning because of the difficulty in assessing and equating for individual differences. Unfortunately, learning is often not characterized well by group data. Individual differences, based on previously unidentifiable differences, systematically affect learning in distinct ways.

The approach to learning offered by Dynamic Pattern Theory (dynamics[1]) overcomes some of the individual differences problems of previous learning theories by identifying intrinsic patterns before learning begins. Dynamics enables the identification of individual differences and shows how learning a new movement pattern is affected by pre-existing patterns, and vice-versa.

Dynamic pattern theory is derived from a physical theory of self-organization and pattern forming called synergetics (Haken, 1977) which assumes that a system has the capacity to self-organize. Order exists on a macroscopic level from the microscopic elements comprising the system. Dynamics refers specifically to coordination of both rhythmic (e.g., Schöner, Zanone, & Kelso, 1992) and discrete (e.g., Schöner, 1989; Walter, Swinnen, & Franz, 1993) movements. The central nervous system achieves coordination through self-organization of abstract, functionally specific equations of motion (Schöner, Zanone, & Kelso, 1992). Coordination can be defined as the process by which the components of movement are temporally organized to produce a movement pattern (Scholz, 1990). Dynamics is used to determine how existing movement patterns are produced and how new patterns are learned. In particular, it addresses the degrees of freedom question - given the

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1 Please refer to the glossary in Appendix A for a definition of underlined terms.

nearly infinite number of combinations by which the neural, muscular, and skeletal components can be organized, how can a relatively limited set of patterns be produced with consistency (Scholz, 1990)? Kelso and his colleagues (Haken, Kelso, & Bunz, 1985; Kelso, 1984; Kelso, Holt, Rubin, & Kugler, 1981; Schöner & Kelso, 1988) developed the use of dynamics to study human movement in an attempt to determine the principles of pattern generation that exist independent of the structure(s) producing the behavior. Dynamics emphasizes the examination of changes over time - either over the short term (in response to environmental influences) or over the long term (through learning or development).

Short-Term Dynamics

This analysis of coordination dynamics allows one to examine the intrinsic changes due to learning during practice of a task. The task most often used involves rhythmic movement of two limbs in a coordinated pattern. Terms specific to the analysis of bimanual coordination have been adopted from their physics origin to describe the relation between two oscillating limbs. In bimanual coordination, the position of one limb relative to the other can be described by the collective variable relative phase. One limb (the right, for example) is used as the reference limb. A full cycle of the right arm would constitute 360° and a movement from peak extension to peak flexion, or vice versa, would be considered 180°. Thus, if one limb is taken as the reference, and the other is measured in degrees relative to the first, the relative position (relative phase) of the left and right limb can be quantified (e.g., see Rosenbaum, 1991, p370, for an illustration).

Previous work (Cohen, 1971; Kelso, 1984; Yamanishi, Kawato, & Suzuki, 1980) demonstrated that two preferred modes of bimanual coordination exist. In-phase coordination (0° relative phase) exists when homologous muscles flex and extend simultaneously. Anti-phase coordination (180° relative phase) exists when non-homologous muscles flex and extend simultaneously. Examination of coordinated movements between limbs has included (a) rhythmic cycling of fingers (Kelso, 1984; Scholz & Kelso, 1990; Zanone & Kelso, 1991, 1992a, 1992b), (b) forearms (Lee, Swinnen, & Verschueren, in press), (c) between arms and legs (Jeka, Kelso, & Kiemel, 1993; Kelso & Jeka, 1992), (d) legs between two people (Schmidt, Carello, & Turvey, 1990), (e) within-limb wrist and elbow movements (Kelso, Buchanan, & Wallace, 1991; Kots & Syrovegin, 1966), as well as (f) various relations among affectors in non-human species (e.g., see Swinnen, Heuer, Massion, & Casaer, 1994, for references).

Both experimentally (e.g., Kelso, 1984) and theoretically (Schöner, 1989) it has been demonstrated that rhythmic limb movements spontaneously switch from the less stable anti-phase pattern to the more stable in-phase pattern when the frequency of movement is increased. Before a transition occurs, other measures can be used to demonstrate a loss of stability of the present pattern. Variability, as determined by the standard deviation of relative phase, increases as the critical frequency is approached. Relaxation time also increases. Without actually observing a phase change, a loss of stability of the phase relation can be determined through examining relaxation times and relative phase variability. Loss of stability is necessary for a change to occur (Schöner, Zanone, & Kelso, 1992).

It is also possible to 'probe' the entire attractor layout by guiding the subject to perform a number of different relative phases between 0° and 180°. This has been done either from memory, after initiating the trial with pacing metronomes (Yamanishi, Kawato, & Suzuki, 1980), or with two visual metronomes (Zanone & Kelso, 1992a). Typically the increments are small (e.g., 15°) and no feedback is given to the subject about performance. Constant error (CE) is measured to determine the bias in performance. It has been demonstrated that subjects have a bias towards producing the two intrinsic patterns and, consequently, CE shows a bias to 0° and 180°. Such probing allows the experimenter to sample the entire range of possible coordination patterns to determine how learning a new pattern affects performance of intrinsic patterns.

Long-Term Dynamics

Researchers working in dynamics have noted some important concepts about learning (Schöner, 1989; Schöner, Zanone, & Kelso, 1992; Zanone & Kelso, 1991, 1992a). Notably, learning involves pattern formation and the emergence of ordered behavior (Zanone & Kelso, 1991). This new ordered behavior develops with the influence of pre-existing ordered patterns. As previously discussed, describing the initial organized state has been difficult for researchers in perceptual-motor behavior. It has been proposed (Swinnen, Walter, Lee, & Serrien, 1993; Zanone & Kelso, 1991, 1992a, 1992b) that to understand learning, the attractor layout must first be defined so that any behavioral changes due to learning can be assessed with respect to the stability of existing patterns. Examination of the experimental literature leads to specific predictions and questions for future research.

Zanone and Kelso's (1992a) subjects practiced a 90° relative phase task to determine how the entire attractor layout changed with learning. Subjects were paced by two visual metronomes - one for each finger. The task was to coordinate the right and left index fingers in the specified pattern. Subjects practiced the task in blocks of 5 trials of 20s each. Four blocks were performed during each session and practice comprised 5 sessions. Between each block, and at the beginning and end of each day, subjects performed a scanning trial in which they performed 13 different relative phases from 0° to 180° in steps of 15°.

At the beginning of practice, subjects tended to produce either 0° or 180° relative phase. The 90° task was being performed consistently by the end of the second day of practice (Zanone & Kelso, 1992a). When delta relative phase (mean deviation from to-be-produced relative phase, called CE here) was plotted for all the coordination patterns probed, 90° was shown to be an attractor. The emergence of 90° as an attractor was considered to be a phase transition on the learning time scale (Zanone & Kelso, 1992a). The attractor layout thus became tristable (0°, 90°, and 180° are all attractors). As practice continued at 90° relative phase, the within-trial variability (standard deviation of relative phase) decreased as did the intrasubject variability (variation in trial to trial variability). The stabilization in performance of 90° during practice coincided with the emergence of 90° as an attractor for nearby phase relations (Zanone & Kelso, 1992a).

Interestingly, probing revealed that 180° relative phase destabilized as practice continued. Zanone and Kelso (1992a) proposed that there may be a limit to the number of patterns that can exist in the attractor layout because the new pattern becomes a strong enough attractor to destabilize the least stable existing pattern (e.g., 180°). A seven day 'recall' test was performed and no significant differences were found between the last day of practice and performance on recall.

For some subjects 90° relative phase was an attractor initially. For these subjects, 180° destabilized more quickly and a bistable attractor layout emerged at 0° and 90°. Theory predicts that even for those subjects with only bistable intrinsic dynamics, 180° will eventually destabilize to produce a bistable attractor layout similar to the aforementioned subjects (Schöner, 1989).

Using the same experimental method, Zanone and Kelso (1994) had subjects perform 90° or 135° (if 90° was shown to be an intrinsic attractor) and then used a transfer test to 270° or 225° (270° relative phase is the symmetrical opposite of 90°, as 225° is to 135°). They were able to demonstrate that learning was not specific to the limb (invariant across components) as the symmetrical opposite (that was not practiced) also became a basin of attraction. In addition, it was shown that a quantitative shift occurred from 90° to 135° for those practicing 135°. A new attractor emerged at 135° because of a shift of the attractor from 90° to 135°. It is not clear from the results whether 180° destabilized. The reported graphs indicate some destabilization, but no conclusions were made by the authors (Zanone & Kelso, 1994)

Lee, Swinnen, and Verschueren (in press) had subjects practice rhythmic movements of the forearms with overall timing paced by a single auditory metronome. Subjects practiced 90° relative phase by cycling the forearms. One forearm moved with an amplitude of 90° and the other maintained an amplitude of 60°. Subjects were also provided with concurrent visual feedback in the form of a Lissajou figure with the displacement of the two arms plotted on the ordinate and abscissa (Lee, Swinnen, & Verschueren, in press). A practice session consisted of 4 test trials, one preceding each of 3 blocks of 20 practice trials and one following the last practice session. Twelve test trials followed the last block of practice. Subjects showed an initial destabilization of 180° relative phase on the first day but demonstrated recovery and no further destabilization later in practice. This result contradicts the findings of Zanone and Kelso (1992a, 1994) suggesting that new patterns can be added without destabilizing intrinsic ones (Lee, Swinnen, & Verschueren, in press). As well, no plateau in learning the 90° pattern was evident even after three days of practice and no retention test was used to assess the permanence of learning the 90° pattern.

The influence of intrinsic attractors on initial learning of a 90° pattern and the subsequent influence of 90° on the intrinsic patterns remains unclear. Zanone & Kelso (1992a, 1994) demonstrated a destabilization of 180° as practice of 90° continued. Lee, Swinnen, and Verschueren (in press) showed an initial destabilization of 180° on the first day but no such effects were seen later in practice of 90°. The 180° pattern destabilized for subjects in the Zanone and Kelso (1992a) study concomitant with a plateau in learning the 90° pattern. It is possible that destabilization of 180° did not occur for subjects in the Lee, Swinnen, and Verschueren study (in press) because learning of 90° had not reached a plateau.

Schöner, Zanone, & Kelso (1992; Schöner, 1989; Zanone & Kelso, 1992a, 1992b, 1994) propose, both theoretically and experimentally, that the to-be-learned pattern will be influenced by and will influence the existing attractor layout. The general purpose of the following experiments is to examine the reciprocal influence of intrinsic dynamics on learning new patterns. In the first experiment, the pattern was equidistant from both attractors (i.e., 90°). The second experiment compared learning one of two patterns that were closer to one attractor than the other. Once well learned, the new pattern becomes an attractor and is predicted (Schöner, Zanone, & Kelso, 1992) to destabilize the less intrinsic attractor. Specifically, in Experiment 1, it is predicted that the anti-phase (180°) pattern will destabilize during acquisition of the to-be-learned (90°) pattern, as subjects will be practicing the task for 4000 cycles over 6 practice sessions. In Experiment 2, due to greater competition from 0°, the 45° pattern will not be learned as quickly as 135° even though both are 45° from an intrinsic attractor. The purpose of the present experiments was to test these predictions.

Once well learned, the new pattern should become an attractor such that it may, in turn, influence the performance of the intrinsic patterns. In addition, to further investigate the permanence of learning, the present experiments include a four week retention test. The retention interval is longer than previous studies (e.g., one week in Zanone & Kelso, 1992a; none in Lee, Swinnen, & Verschueren) and should reveal the extent to which the new pattern is learned as well as any change in the intrinsic patterns due to practice effects. With a longer practice period and retention interval, it is believed that the following experiments will resolve the conflicting evidence from the previously reported studies.

Experiment 1

The primary purpose of the first experiment was to assess the influence of the intrinsic attractors on learning 90° early in practice and any reciprocal effect when 90° was well practiced. Zanone and Kelso (1992a) reported a destabilization of 180° concurrent with the emergence of 90° as an attractor. Contradictory results were reported by Lee, Swinnen, and Verschueren (in press) with a slightly different task and procedure for sampling the attractor layout. In this experiment, each subject performed over 4000 cycles of practice. The conflict created by the aforementioned studies should be resolved with the increased practice and longer retention interval. Additional purposes were to determine if (a) there was a plateau in learning, (b) if there was a warm-up decrement at the beginning of each session (c.f., Lee, Swinnen, & Verschueren, in press), and (c) if there was any change between the last day of practice and the four week retention test.

Method

Subjects

Seven kinesiology students at McMaster University were paid $30 for their participation in the study. All were right handed and ranged in age from 21-24.

Apparatus

The task was to displace two linear sliding devices toward and away from the body midline using rhythmical movements of the two arms. A wooden dowel (3 cm in diameter) was attached vertically to each sliding device for the subjects to grasp. The sliding devices were of the type found in kitchen drawers with an arm riding on ballbearings inside a casing thus restricting movement to linear displacements in one plane (see Figure 1). Subjects were seated at a chair centered between the two mechanical arms at a height such that their forearms were approximately parallel to the table when grasping the wooden dowels. Linear potentiometers (BEI Electronics Company, model 612R12KL.08) were attached parallel to the sliding devices to encode displacement. Subjects were instructed to complete one cycle of the movement coincident with the beats of an auditory metronome. The metronome operated at 1 Hz. The amplitude required to match the task criterion (e.g., 32 cm for a full 360° cycle) was marked on the wooden base of the apparatus. The apparatus allowed for movement of the arms a minimum of 2 cm beyond the criterion both medially and laterally. Subjects were instructed to always coincide the arrival of the right arm at the body midline with the beat of the metronome, regardless of experimental condition.

A computer monitor provided on-line feedback about the movement in the form of a Lissajou figure. Right arm displacement was plotted on the abscissa and left arm displacement on the ordinate. Although the feedback could be given concurrently, it was only given as terminal feedback after each trial (see Appendix D for sample Lissajou figures).

An 80486 microprocessor was used to sample data at a frequency of 200 Hz. The computer was used to start and end each trial, control onset and offset of the metronome, and record the data[2]. Point estimates of relative phase, observed at peak flexion and extension of the right arm, and amplitude of movement at the peaks were recorded (Scholz & Kelso, 1990). The data

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2 Programme software was written in Lab Windows.

were saved directly to the hard drive and subsequently downloaded as an ASCII file or printed for further analysis.

Procedure

Subjects were initially given written instructions (see Appendix B) that outlined the purpose of the experiment and explained how the three movement patterns (0°, 90°, & 180°) were to be performed. Subjects were subsequently asked to describe how they thought they were to perform the 90° pattern to ensure they understood the instructions. Finally, subjects were encouraged to use the apparatus while reading the instructions in order to familiarize themselves with the movement of the mechanical arms. The primary task was to produce a rhythmical pattern in which the right hand lead the left by one-quarter of a cycle (90° relative phase). The amplitude for both arms was the same.

Fifty-five trials were performed during each practice session (see Table 1 for a summary of trials). The first six trials consisted of two 0°, two 180°, and two 90° patterns without feedback to establish levels of performance before practice. Forty-five practice trials were then performed with terminal visual feedback. The last four trials, which duplicated the first four trials, were performed without terminal or concurrent feedback (two at 0° and two at 180°). These procedures were replicated on each of six days of practice, separated by no more than two days of rest (see Table 1).

To begin a trial, subjects placed the right arm at the 'in' position (body midline) and the left arm was placed appropriately for the required relative phase. For 0°, the left hand would also be at 'in'; for 90°, the left hand would begin at the 'middle' position; and for 180°, the left hand would begin at the 'out' position (see Figures 1 & 2). Once the subject was ready, the experimenter would initiate the next trial. After each trial, the subject observed their feedback while the experimenter saved the trial to disk. The next trial was begun when the subject was ready. Typically, the inter-trial interval was 5 - 10 s.

Terminal visual feedback was given as a Lissajou figure on the computer screen. The subject observed the trace of the just completed trial over the template of the task goal of a circle (see Appendix D for sample figures). After every fifth trial, the subject was given augmented feedback on how the completed movement differed from the task goal. The augmented feedback was given verbally by the experimenter indicating deviations (including CE and VE) of the performed pattern from the required task. The experimenter then answered any questions asked by the subject.

A retention test of 6 trials was performed four weeks after the final practice session. The protocol was the same as for the initial 6 trials of practice except that no augmented feedback was given during performance of the 90° pattern.

Data Analysis

Relative phase was calculated as the position of the left limb relative to the right at peak flexion and extension normalized for velocity. Relative phase constant error (CE) and standard deviation of constant error (variable error) were recorded within a trial for each of the goal patterns (i.e., goal relative phases of 0°, 90°, or 180°). Trial means were computed across five trials for the 45 practice trials and over two trials for the no feedback trials (pre- and post-practice). The mean for the last 5 trials of the practiced pattern was used as the post-test value as no trials without feedback were performed at the end of practice (see Swinnen, Lee, & Serrien (1994) for a discussion of learning a bimanual coordination task with and without feedback).

Figures 3 and 4 present an organizational outline of the data analyses. The data were first examined on an individual subject basis, then by group. Note that the analyses for group data were done for both |CE| and VE only when appropriate. Constant error was used for individual subjects so that biases in performance accuracy could be assessed. For the group data, |CE| was used to avoid the possibility of CEs for different subjects summing to zero.

A three-factor (Day (6) by Time (2) by Pattern (3)) repeated measures analyses of variance (ANOVA) was used to calculate overall effects for the performance data. Subsequent ANOVAs were used to determine differences between means for significant interactions (refer to Figure 4). The ANOVAs were used to determine (a) the difference between intrinsic patterns, (b) the change across days for the 90° pattern, (c) differences between the three patterns for each day, and (d) change on the four week retention test. Post-hoc Tukey HSD tests were used to determine differences between means on these subsequent ANOVAs.

Results and Discussion

Individual Data

Qualitative individual data analysis is important for assessing similarity between subjects and the different learning curves. Therefore, a description of the characteristics of the individual data is given first followed by an analysis of the group data using inferential statistics.

Figures 5 a, b, and c show constant and variable error scores for all three patterns for each subject. Performance on each day of practice is expressed on both pre- and post-practice. A single value expresses the retention score. Large differences were exhibited between subjects in both CE and VE and there was no clear relationship between the two variables within each subject, particularly during the first three days of practice. No subject demonstrated large changes from the last day of practice to the four week retention test.

<u>0° vs. 180° - Accuracy (CE).</u>

In comparing the performance of the 0° and 180° patterns throughout practice, the 180° pattern is performed more accurately than 0° for all subjects except NH (for which there is no clear bias). This trend also exists on retention. During acquisition, the differences were small for some subjects, but for others the differences were substantial. For both intrinsic patterns, no subject's performance changed substantially across days.

In retention there was no clear trend across subjects. For WC, there was a small improvement for 0° and 180° from the last trials of practice to retention suggesting practice of the 90° task had a negative effect on performance of the intrinsic patterns. For NH, accuracy for the in-phase pattern got poorer from Day 6 to retention but the 180° pattern was performed more accurately in retention when compared to Day 6 of practice. No explanation can be found for this dichotomous result. Conversely, KA exhibited improved performance on retention for the in-phase pattern and no change for anti-phase. In general, there was no systematic change in the accuracy of performance for the intrinsic patterns from the end of practice to retention four weeks later.

0° vs. 180° - Stability (VE).

The in-phase pattern was performed with more stability for most subjects (e.g., KA, MS, NH & WC). However, neither pattern became less stable across days. One subject improved across all six days (KA) while some improved across the first three days only (e.g., CG & WC). No subject exhibited a distinct pattern of improvement or decline within each day. Only two subjects (LM & WC) demonstrate similar changes in stability for both patterns, however the direction of change varied across days.

For four subjects (CG, KA, LM & WC), stability on retention was the same as the last day of practice. The other three subjects (KH, MS & NH) exhibited lower variability in performance on retention than the last day of practice. This suggests that there may have been a temporary effect on performance during practice which was not present on the four week retention test.

90° - Accuracy (CE).

Each subject was different in their initial performance bias. All subjects, however, were biased away from 0° early in practice. Most produced patterns were near 90°, 180°, or 270° with some trials being a combination of two or three of the patterns (see Figures 5 a, b, & c).

All subjects improved across days. However some reached a plateau in performance earlier than others (not a learning plateau since performance continues to stabilize). No improvement is apparent for LM after Day 1, no improvement for KH after Day 2, and all others took 3 or more days to plateau. Only WC and LM had a negative constant error for any trials. The other 5 subjects performed the 90° pattern with a positive CE (i.e., biased toward 180°). This could be indicative of greater competition from 0° biasing performance toward 180° even late in practice.

It is also valuable to compare performance of the practiced pattern to performance of the intrinsic patterns. For all subjects, accuracy for the 90° pattern on the last day was similar to that for the 0° and 180° patterns. Those with low CE for the 0° and 180° patterns (KA & LM) also had low CE for the 90° pattern. The one exception was MS who exhibited lower CE's for 90° than for in-phase or anti-phase.

Every subject seemed to have a different approach or strategy for performing the required task. MS did a 270° pattern often so that the terminal feedback appeared correct but was actually done "the wrong way" (i.e. the left hand lead the right instead of the right leading the left). NH and WC also performed with a CE of 180° on the first day (i.e., a 270° pattern). CG had to be encouraged to move faster, creating large inter-trial variability. For KA and KH it was a gradual reduction of CE from 90° to less than 15°.

Performance on the retention test was comparable to the last day of practice for all subjects. No forgetting or loss of stability was evident after 4 weeks without practice.

<u>90° - Stability (VE)</u>.

For all but one subject (NH), the plateau in stability occurred below a standard deviation of 15° degrees. The profile for each subject before the plateau is quite different. Most (CG, KA, NH & WC) improved gradually across the first four or five days. Day 1 of practice was highly variable for three subjects (CG, MS & WC). Surprisingly, the remaining subjects were relatively stable in their performance. Large variable error during practice of a new pattern usually indicates a search strategy through a number of different patterns as the subject tries to find the appropriate phase relationship between the two oscillating limbs.

No subject exhibited a large increase in variability on retention. One subject (LM) actually performed the 90° pattern with greater stability on retention than in practice.

Summary of Individual Data

When both CE and VE are taken together, there was no systematic trend for subjects with low CE or VE on intrinsic patterns to begin with low CE or VE in practiced patterns. Subject MS, in particular, had a high CE and low VE early in practice because many trials had a CE of 180°.

Subjects seemed to use different strategies to perform the 90° pattern. KA showed little change in variability throughout practice even with large changes in CE across the Days 1 and 2 particularly. This suggests a strategy of "controlling" the variability in performance while attempting to improve error. LM performed the 90° pattern with low CE and VE early in Day 1 indicating 90° may already have been in LM's repertoire. NH had large changes in CE and VE throughout practice suggesting lapses in concentration or trouble matching the metronome and thus affecting stability of performance. WC and MS both performed a 270° pattern early in practice but began approximating 90° before the end of Day 2.

Group Data

The individual data were pooled for analyses of variance. The intrinsic patterns did not change dramatically through practice although some significant differences were found. The 90° pattern followed a typical learning curve (see Figures 6 & 7), with |CE| and VE reaching a plateau by Day 4 of practice. The four week retention test revealed no forgetting (performance loss) for the 90° pattern.

Accuracy (|CE|).

The overall ANOVA of Day(6) by Time(2) by Pattern(3) showed significant main effects for Day, Time, and Pattern There were significant two-way (Day by Time, Day by Pattern, and Time by Pattern) interactions as well as a significant three-way interaction (see Figure 6 & Table C-1). Based on this information, further analyses of variance were performed to determine the differences between groups on the interactions (see Figure 4 for outline). Note that most of the variance is accounted for by the Day and Pattern main effects and the Day by Pattern interaction (refer to the column entitled 'Omega Squared' in Table C-1). The specific effects of interest were (a) the change over time of the practiced pattern and the intrinsic patterns, (b) the difference between the three patterns within each day, and (c) the difference between the last day of practice and retention.

The three-factor ANOVA of Day(6) by Time(2) by Pattern(2) for 0° and 180° revealed two significant effects (see Table C-2). The first was a main effect for Time showing an increase from pre-test to post-test. This indicates a loss of accuracy in performing the intrinsic patterns when practice of a new pattern occurred between tests. The second effect was a significant Day by Pattern interaction, indicating that accuracy of 0° degraded across practice days and accuracy of 180° improved. Performance of the 90° pattern requires the right hand to the lead the left by one-quarter of a cycle. This right hand lead may have transfered to performance of the 0° pattern yielding an increase in |CE| as it is biased toward 90°.

The Day(6) by Time(9) ANOVA for the 90° pattern revealed significant Day and Time main effects as well as the Day by Time interaction (see Figure 5 & Table C-3). The significant interaction indicates that a plateau is reached as the learning rate slows during the latter days of practice. More specifically, there is little change across time on the last two days, however, there was a great deal of change during the first two days of practice.

To investigate pattern differences within each day, six two-factor Time(2) by Pattern(3) ANOVAs were performed (see Table C-4).

Day 1 - There was a large improvement for the 90° pattern from pre- to post-test yielding a Time main effect. Post-hoc analysis of the Pattern main effect determined |CE| for 90° was greater than the |CE| for 0° and 180°. The significant Time by Pattern interaction was due to improvement for the 90° pattern and relatively stable performance of the 0° and 180° patterns.

Day 2 - There was no Time main effect (or Time by Pattern interaction) although changes in |CE| were still quite large for the 90° pattern. Again, the pattern main effect was due to a higher |CE| for 90° than 0° and 180°. The absence of a significant time main effect was surprising given the magnitude of change (see Figure 6) but was likely due to the large intersubject variability.

Days 3 & 4 - There were no significant main effects or interactions.

Day 5 - The significant Time by Pattern interaction was a result of an increase in |CE| for the 180° pattern and a decrease in |CE| of similar magnitude for 90°.

Day 6 - Post-hoc Tukey HSD for the Pattern main effect revealed the |CE| for performance of the 180° pattern was significantly smaller than for performance of 0° and 90° yielding a Pattern main effect.

Retention data was analyzed using a Time(3) by Pattern(3) ANOVA (see Table C-5). The three levels of Time were pre-test Day 6, post-test Day 6, and retention. (The retention test occurred four weeks after the last practice session.) There was a main effect for Time and Pattern. Tukey HSD post-hoc revealed that post-test on Day 6 is different from retention and pre-test of Day 6 (which are not different from each other). The pattern main effect is due to a smaller |CE| for 180° than for 0° and 90°. It was unexpected for the 180° pattern to be performed with greater accuracy than 0° as 180° is presumed to be the less stable intrinsic pattern.

Stability (VE).

The overall ANOVA for VE, Day(6) by Time(2) by Pattern(3), revealed significant main effects for Day and Pattern as well as a significant Day by Pattern interaction (see Figure 7 & Table C-6). Further analyses were done to investigate the aforementioned main effects and interaction. The lack of a significant change across time suggests that subjects tended to improve from one day to the next, and not within a day. Contrary to the |CE| data, there was no Time by Pattern interaction as the VE for all three patterns changed similarly from pre-test to post-test. It appears that variability (VE) of the intrinsic patterns improves during intervening practice but accuracy (|CE|), particularly of the in-phase pattern, is negatively affected.

The three-factor Day(6) by Time(2) by Pattern(2) ANOVA for 0° and 180° revealed a significant main effect for Day, Time, and Pattern as well as a Day by Time interaction (see Table C-7). Tukey HSD post-hoc determined that Day 1 VE was significantly higher than all other days. This is primarily due to a high VE on the pre-test trials of Day 1 (mean for Day1-Time1 = 16.44°). The main effect for Time was not investigated further because it was not significant in the initial analysis. Again, this reinforces the result from the previous analysis that stability improves from pre- to post-test for both patterns. The in-phase pattern was performed with greater stability than the anti-phase pattern. The significant Day by Time interaction indicated a change from pre-test to post-test across days, due primarily to the high VE for Day1-Time1 for both 0° and 180° and the lack of change within a day for subsequent days.

Significant Day and Time main effects were found for the two-factor Day(6) by Time(9) ANOVA for the 90° pattern (see Table C-8). Post-hoc analysis determined that Day 1 VE was much higher than subsequent days. As well, Day 2 was greater than Days 5 and 6. No significant differences were found between means within a day. The interaction of Day by Time was not significant indicating the reduction in VE within each day occurred for all practice days.

Six two-factor Time(2) by Pattern(3) ANOVAs were performed (one for each day of practice) (see Table C-9).

Day 1 - Only the Pattern main effect was significant. The VE for the 90° pattern was greater than the VE for the intrinsic patterns. This result was expected as there was a high variability in performing the new pattern early in practice.

Days 2, 3, 4, 5, and 6 - For all days, only the Pattern main effect was significant. Variability of the 90° pattern was never quite as low as the intrinsic patterns. This suggests that subjects were never able to learn the 90° pattern well enough for it to become as stable as the intrinsic patterns.

There was a significant Pattern main effect for the two-factor Time(3) by Pattern(3) ANOVA on the retention data (see Table C-10). Post-hoc analysis revealed the VE for the 90° pattern was greater than the VE for 0° and 180° (which are not different from each other).

<u>Summary of Group Data.</u>

Overall, particularly for the group data, there were many more differences for |CE| than VE. VE for all three patterns changed little within a day but improved across days. Absolute CE improved both within and across days for 90° but accuracy decreased for intrinsic patterns across days. There was no forgetting for any pattern in accuracy or consistency. Accuracy of performing 90° is not different from 0° and 180° by the end of practice but stability was never as good for the 90° pattern.

There was a temporary effect of practicing 90° on the intrinsic patterns after 45 trials. The CE was biased towards 90° for both intrinsic patterns. Stability was unchanged, however. This is contradictory to the theoretical predictions of Zanone and Kelso (1994) that the 180° pattern destabilizes concomitant with the emergence of the 90° pattern as an attractor.

Experiment 2

The purpose of the second experiment was to further examine the reciprocal influence of intrinsic attractors and to-be-learned patterns. In this study, the to-be-learned patterns were 45° and 135°. Each pattern is 45° from one intrinsic attractor and 135° from the other (see Figure 8). Dynamics theory (Zanone & Kelso, 1994) predicts that the learning rate for a new pattern is inversely related to the stability of the closest intrinsic attractor. Therefore, learning rate should be faster for the 135° pattern than the 45° pattern because it is near the less stable intrinsic attractor, 180° (Zanone & Kelso, 1994).

As both the to-be-learned patterns are equidistant from an intrinsic attractor, there should be no difference in the type of change that occurs. That is, there should be an abrupt, qualitative, shift in 'phase space' because the to-be-learned pattern is so far (in phase-space, as measured in degrees of relative phase) from the intrinsically stable attractors (Zanone & Kelso, 1994). An abrupt change is predicted to occur if the to-be-learned pattern is 60°-90° from an intrinsic attractor. A smooth (quantitative) shift should occur if the to-be-learned pattern is near an intrinsic attractor. As well, there may also be some destabilization of 180° during practice of 135° due to the proximity of the two patterns and because 180° is a less stable attractor.

Two groups of 6 subjects were required to learn either 45° or 135° over 4 practice sessions. Practice was similar to Experiment 1 with subjects performing 45 practice trials on each day, in blocks of 15 trials. However, different from Experiment 1, subjects performed two in-phase and two anti-phase trials between each practice block without feedback to assess the stability of these patterns during practice. Subjects practiced on four separate days as Experiment 1 has shown that performance of the new pattern stabilized by the fourth day.

Method

Subjects

Twelve students were recruited from the Kinesiology Department at McMaster University and were paid for their participation. Subjects were randomly assigned to one of the two experimental groups. All subjects were right handed and between the ages of 20 and 24.

Apparatus & Procedure

The apparatus and procedure were the same as in Experiment 1 except: (a) two groups practiced either 45° or 135° over 4 sessions, (b) there were four no feedback trials (2 in-phase, 2 anti-phase) between blocks of 15 practice trials, and (c) the four week retention test had only 2 trials for each pattern (see Table 2).

Data Analysis

As in the previous experiment, data were categorized first by individual subjects and then by group. The individual subject data are reported descriptively (see Figure 9). As with the data in Experiment 1, individual data were reported using CE as a measure of accuracy. Absolute CE was used to measure accuracy for group analysis. The group data were analyzed with a four factor ANOVA and subsequent ANOVAs for three- and four-way interactions (see Figure 10 for organization of the analyses). More specifically, the data were separated so intrinsic patterns were examined independent of the to-be-learned patterns. A Day by Pattern analysis was done to determine the days on which the practiced pattern was significantly different from the intrinsic patterns. Additionally, retention data was analysed separately for both the practice groups. A specific analysis was not used to compare the two practice groups on the intrinsic patterns because the Group by Pattern interaction was not significant for either four-factor ANOVA.

Results and Discussion

Individual Data

As in Experiment 1, there were many different learning curves exhibited by the subjects during the four practice sessions. Notably, half of the subjects in both groups had a strong bias to perform 90° late in practice (particularly for the group practicing 135°). For the intrinsic patterns, the 180° pattern was performed more accurately than the 0° pattern for 8 of the 12 subjects. However, there were no obvious differences in stability of performing either pattern. No consistent changes, and certainly none of any great magnitude, were found from Day 4 to the four week retention test for any pattern.

Again, the pattern of learning was different for all 12 subjects so the process of examining individual data may provide advantages to discovering how subjects learn a new task that cannot otherwise be determined from pooled data. Figures 11a, 11b, 12a, and 12b show the constant and variable error scores for each subject across the four practice sessions and retention.

0° vs. 180° - Accuracy (CE).

For the group practicing 45°, there were no clear trends among the 6 subjects for either pattern. Only DM showed similar performance for both patterns. Two subjects (BR & PM) demonstrated more accurate performance of 180° than 0° while no subject was more accurate performing the 0° pattern. There was no consistent increase in CE over days but some examples exist within days (e.g., DM & MC).

For the group practicing 135°, 3 subjects (KD, MR & TK) exhibited CE values that were similar for both patterns, as was the change in CE throughout practice. Consistent differences in accuracy of the intrinsic patterns were observed for LC and SS. Only KD and TK remained fairly consistent within and across days. For all six subjects, the anti-phase pattern was performed more accurately on retention than the in-phase pattern.

On retention, the in-phase pattern had a greater CE than the anti-phase pattern for all subjects. Again, some show improvement from the end of practice (particularly AG & DM) for both patterns but for the most part only one of the two patterns shows improvement. No subject performed less accurately on both patterns for retention as compared to Day 4 of practice.

Intrinsic Pattern - Stability (VE).

For the group practicing 45°, the variability for all subjects was similar for both patterns. There were no differences between the stability of groups, however changes for one pattern do not parallel the other. There was little change over days and no trend within each day was found for a consistent increase or decrease in stability.

The stability of performance in retention was very similar for both patterns and when compared to the last day of practice for all subjects (see Figures 11a, 11b, 12a, & 12b).

Similar changes were found for the group practicing 135°. Not only were the variabilities similar but they changed in the same direction. No change was observed across days except that Day 1 often had higher variability than Days 2, 3, and 4.

On retention, change in variability was mixed. For some (AS, LC & TK) there is no change and for others (MR & SS) there was an increase in VE from the last day of practice to retention.

<u>Practiced Pattern (45° & 135°) - Accuracy (CE).</u>

No clear trends were found for the group practicing 45°. Most subjects (BR, DC, DM & PM) were biased toward 90° (CE = +45°) early in practice before the pattern stabilized closer to 45° (CE = 0°). Two subjects (DC & PM) never approached 45°. The other four subjects were able to maintain a low CE for at least the last day. Two subjects (DM & PM) exhibited much greater variation in CE than did the other subjects.

For the group practicing 135°, subjects MR and TK began practice by performing the 180° pattern (CE = +45°) and both went to 90° (CE = -45°). Subject TK worked toward 135° while MR remained at 90° throughout practice. LC and SS had little difficulty with the task as their CE was always less than 45°. KD had particular difficulty on Day 1 but performance stabilized during Day 2 although KD was never able to move away from 90°. AS took 2 days to approximate the 135° pattern because many of the trials were performed with a CE of 180°. Even when performance stabilized (Day 3) CE was -45°. Three subjects were able to approximate 135° while the other 3 remained at 90° (CE = -45°).

In retention, CE was within 10° degrees of last day of practice for all subjects with most being similar or less accurate on retention. That the subjects were able to maintain accuracy in performing the practiced pattern after a 4 week no-practice interval implies the learning was well retained.

<u>Practiced Pattern (45° & 135°) - Stability (VE).</u>

For most subjects practicing 45°, only small fluctuations in VE were seen during Days 1 and 2 and variability stabilized by Day 3. Subjects DC & BR are the exceptions, particularly on Day 1. This result suggests that subjects were having little difficulty producing the required pattern, or they were unwilling to change their present (stable) pattern to match the criterion pattern. It appears that the former is the case. Only subject PM had considerable difficulty performing the required task (indicated by CE). However, it appears as though PM was unable to change from this pattern as VE was never very large. A large VE would indicate a lack of stability and thus create an environment for pattern change. The two subjects (DC & PM) who continued to approximate the 90° pattern were also the only two subjects to have variable errors consistently above 15°. Therefore, either there was still some effort on their part to change the pattern, or they were inherently unstable and unable to produce the required pattern.

The VE data for the group practicing 135° parallels the CE results in that there was very little similarity between any of the subjects. AS and MR did not stabilize VE until Day 3. LC and KD had high VE for Day 1 only, whereas SS and TK stabilized their performance before the end of practice in Day 1. VE stabilized by the end of Day 3 for all subjects.

In retention, two subjects that practiced 45° (DC & PM) and two subjects that practiced 135° (KD & LC) had a lower VE on retention while the other subjects exhibited no change on retention. No subject exhibited a regression in stability from the last day of practice to retention.

Summary of Individual Data.

Performance of the required pattern stabilized by Day 4 of practice for all subjects. Some subjects (e.g. AS, KD & MR), however, continued to perform a pattern close to 90°. The resulting high CE and low VE indicates an unwillingness or inability for these subjects to alter their pattern (as would be demonstrated by an increase in VE) even when presented with feedback indicating large errors. The four week retention test demonstrated that the pattern was well learned for all subjects even though practice was reduced to four days from six in Experiment 1.

Group Data

The group means for both dependent measures (|CE| and VE) exhibited typical learning curves for the practiced patterns, nearing a plateau by the fourth day of practice (see Figures 13 & 15). No differences were found between groups on the practiced patterns for VE and, though non-significant, |CE| for 135° was greater than the |CE| for 45°. As in Experiment 1, no changes were observed from the last day of practice to retention.

Accuracy (|CE|).

The overall ANOVA of Group(2) by Day(4) by Time(2) by Pattern(3) revealed no group differences or interactions of variables with Group. For this analysis the three patterns were 0°, 180° and the practiced pattern. Thus the analysis was not a complete factorial design as 45° and 135° were nested within group[3]. There were significant Day, Time, and Pattern main effects and no three- or four-way interactions (see Figures 13, 14 & Table E-1). There were two two-way interactions of Day by Pattern and Time by Pattern. To further investigate these main effects and interactions additional ANOVAs were performed (similar to Experiment 1) with subsequent Tukey HSD post-hoc tests to determine differences between means.

For the four-factor ANOVA (Group(2) by Day(4) by Time(4) by Pattern(2)) of 0° and 180°, main effects were found for Time and Pattern as well as interactions for Group by Day and Group by Time (see Figure 14 and Table E-2). A main effect for Time, but not Day, suggests that |CE| increased within each day but did not change across days. The interactions of both Day and Time with Group were not investigated further because there was no Group main effect or interactions with Group for the initial ANOVA.

The three factor ANOVA of Group(2) by Day(4) by Time(9) for the practiced patterns revealed main effects for Day and Time. There was no Group main effect and no interactions (see Figure 13 & Table E-3). The significant improvement for both groups across days and within days demonstrates that performance improved during each practice session and between practice sessions. Absolute CE for Day 1 was significantly greater than Days 2, 3, and 4. As well, the |CE| for Day 2 was greater than Day 4. For Time, the means at Times 1 and 2 were significantly greater than the means at

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3 Note that the intrinsic patterns were sampled at 4 different times and there were 10 means for the practiced pattern (1 at pre-test and 9 for practice). However, comparisons were only made pre- and post- practice for this analysis.

Times 7 and 9. However, the Time effect has little practical significance when pooled across days, it is the within day changes for each day that are important.

Four three-factor Group(2) by Time(2) by Pattern(3) ANOVAs were performed - one for each day of practice (refer to Table E-4).

Day 1 - The Pattern main effect indicates |CE| for the practiced pattern is greater than |CE| for intrinsic patterns. The Time by Pattern interaction showed |CE| went unchanged from pre- to post-test for the intrinsic patterns and decreased for the practiced pattern. This result was expected as practice should decrease |CE| for 45° and 135° pattern and accuracy of intrinsic patterns was predicted to get worse after practice of another pattern.

Day 2 - The effects were the same as Day 1.

Day 3 - The effects were the same as Day 1.

Day 4 - Only the Pattern main effect is significant as the |CE| for the practiced patterns is still greater than 0° and 180°. However, the absence of a significant Time main effect or interaction of Pattern by Time on the last day of practice between either practiced pattern and the intrinsic patterns suggests learning for the practiced pattern had reached a plateau. If improvements were still occuring an interaction between the decreasing |CE| or VE for the practiced pattern and the relatively stable performance for 0° and 180° would be expected. However, significant differences were still observed between practiced patterns and intrinsic patterns demonstrating 0° and 180° were still performed with more stability than the newly learned patterns.

The retention data for the group practicing the 45° pattern was analyzed using a two factor Time (3) by Pattern(3) ANOVA. No significant effects were found (see Table E-5). Thus, |CE| for all three patterns (0°, 45°, & 180°) were not different nor do they change significantly across Day 4 pre-test, Day 4 post-test, and retention.

A similar ANOVA was done for the group practicing 135°. There was a main effect for pattern. Post-hoc Tukey HSD indicated the |CE| for 135° is greater than |CE| for intrinsic patterns. There was no main effect for time showing no change across pre- and post-test of Day 4 and retention.

Stability (VE).

The overall ANOVA (Group (2) by Day(4) by Time(2) by Pattern(3)) for VE revealed main effects for Day and Pattern. A significant four-way interaction was found as well as three-way interactions for Group by Day by Time and Group by Time by Pattern. The Day by Pattern interaction was also significant (see Figures 15, 16 & Table E-6). Because of the high level four- and three-way interactions, follow-up ANOVAs were done to determine the nature of the group interactions. Again, however, there were no differences between groups. There was no Time main effect or two-way interactions with Time. However (as previously mentioned) the three-way Group by Day by Time and Group by Time by Pattern and four-way Group by Day by Time by Pattern interactions were significant. This indicates that the two groups are differentially affected by manipulations of Day and Time when performing the practiced pattern and the intrinsic patterns.

The four-factor ANOVA of Group(2) by Day(4) by Time(2) by Pattern(2) for 0° and 180° revealed no significant main effects or interactions (see Figure 16 & Table E-7). These results indicate that changes in VE of both intrinsic patterns were small and parallel for both groups. It is interesting to note that the Day(4) by Time(2) by Pattern(2) interaction approached conventional levels of significance, suggesting changes in the 0° pattern across days and time are different from changes in the 180° pattern. However, an examination of Figure 16 does not reveal any distinct differences.

For the Group(2) by Day(4) by Time(9) ANOVA on the practiced patterns, only the Day main effect was significant. No improvement in VE within each day, reinforced by no Day(2) by Time(9) interaction, indicated subjects improved between days but not within each day for stability (see Figure 15 & Table E-8). The Group by Day interaction approached conventional levels of significance. Significance was likely not reached due to the high intersubject variability early in learning, particularly for the group practicing 135°. The difference between Groups can be seen particularly in the first two days (see Figure 15).

Four three-factor Group(2) by Time(2) by Pattern(3) ANOVAs were performed - one for each day of practice (see Table E-9).

Day 1 - There was a significant Pattern main effect. The Group(2) by Time(2) by Pattern(3) interaction approached significance and was likely caused by a large increase in VE for the 135° group from pre- to post-test (25.2° at pre-test and 46.5° at post-test). Post-hoc Tukey's (A) revealed VE for both practiced patterns is greater than intrinsic patterns which are not different from each other. There was no Group main effect or Group by Pattern interaction indicating means pooled across time are not different for either group.

Day 2 - There was a significant Pattern main effect with means for practiced patterns significantly greater than the intrinsic patterns. Again, no Group main effect or Group by Pattern interaction.

Day 3 - There was a significant Pattern main effect.

Day 4 - There was a significant Pattern main effect and a significant three-way (Group by Time by Pattern) interaction. As can be seen in Figure 11, there was a distinct interaction of Group with Time on the practiced pattern. The group practicing 45° improved slightly (VE decreased) during Day 4 while VE increased for the group practicing 135°.

The retention ANOVA for the group practicing 45° revealed a significant Pattern main effect. The VE for the practiced pattern is greater than the VE the for intrinsic patterns. There was no main effect for time, however (see Table E-10).

The ANOVA for 135° practice group (Time(3) by Pattern(3)) on retention revealed a significant main effect for Pattern demonstrating higher VE for 135° than the intrinsic patterns. A significant Pattern by Time interaction indicates a higher VE for 135° at Day 6 post-test but a lower VE at Day 6 post-test for 0° as compared to Day 6 pre-test and retention (see Figures 15, 16 & Table E-10).

Summary of Group Data.

For the intrinsic patterns, VE did not change within or across days, but |CE| increased within each day suggesting a temporary effect of practicing 45° or 135°. Performance on the to-be-learned patterns stabilized by Day 4 but some subjects maintained a high CE with bias toward the 90° pattern.

Performance on the retention test showed no change for each pattern from Day 4 pre-test to retention.

General Discussion

The present experiments were designed primarily to examine the reciprocal effect of learning new coordination patterns and performing existing patterns. Previous research and theoretical predictions (Lee, Swinnen & Verschueren, in press; Schöner, 1989; Schöner, Zanone & Kelso, 1992; Zanone & Kelso, 1992a, 1994) reported conflicting evidence for destabilization of an intrinsic pattern during learning of new patterns. Having established learning, the primary purposes were to determine if either intrinsic pattern destabilized and if there was any change in performance from the last day of practice to the four week retention test. Experiment 2 was designed to further investigate the reciprocal effect of practiced patterns on intrinsic patterns. Again, a four week retention test was used to examine permanence of learning and the influence of any temporary practice effects. Additionally, the second experiment investigated differences in performing two patterns 45° from different intrinsic attractors. Schöner, Zanone, and Kelso (1992) proposed that 135° would be easier to learn than 45° because of less competition from 180° for 135° than from 0° for 45°.

The discussion is organized into the following sections: (a) learning the practiced patterns, (b) reciprocal influence of practiced patterns on intrinsic patterns, (c) related issues and alternative explanations, and (d) summary with future directions.

a) Learning the Practiced Patterns

The tools of dynamics affords the examination of subjects' performance individually because the initial performance characteristics (attractor layout) can be determined. This creates a foundation such that any change in performance of the entire attractor layout, or selected aspects of it, can be examined throughout the time course of learning a new pattern and compared to the previous performance capabilities. This method has the advantage of providing insight into how learning a new skill relates to previously learned skills. Traditional tools of learning studies, such as a retention test, can also be used to determine the permanence of learning the practiced patterns.

The first goal of Experiment 1 was to establish whether or not subjects could learn a coordination pattern (and reach a performance plateau) with 90° phase offset between the limbs with one auditory pacing metronome and terminal visual feedback (in contrast to the the work reported in Lee, Swinnen, & Verschueren, in press, in which subjects had concurrent visual feedback during practice and no performance plateau was observed). Practice data demonstrated that performance of the 90° pattern stabilized by the fourth day (see Figures 6 & 7). Additionally, the four week retention test showed that subjects maintained accuracy and stability of performing 90°, indicating permanence of learning.

Schöner, Zanone, and Kelso (1992) predicted that a 135° pattern would be easier to learn than a 45° pattern because there would be less competition between 135° and the intrinsic attractor 180° then between 45° and 0°. Competition is believed to negatively influence the ability to learn a new pattern. The closer the to-be-learned pattern is to an intrinsic pattern, the greater the competition. Likewise, the stronger the attractor, all else being equal, the greater the competition (Schöner, Zanone, & Kelso, 1992). Thus, 0° would provide greater competition for learning a 45° pattern than 180° would for 135°, as both to-be-learned patterns are 45° from an intrinsic attractor. The results from Experiment 2 do not support this theoretical prediction. Subjects practicing the 135° pattern tended to have a higher |CE|, although not significantly different, than subjects performing the 45° patterns. As well, VE was not different between the two groups (see Figures 13 & 15).

The retention data was unequivocal in that no degradation in stability or accuracy was discovered after four weeks of no practice, indicating that both patterns were well learned. Taken together with the Day 4 results, it can be concluded that, although the 45° pattern may not have reached a plateau in learning, both the 45° and 135° pattern were well learned. This result is somewhat surprising due to the length of time between practice and retention but it is complementary to the work of Zanone and Kelso (1992a), which showed no performance decrement in a one week retention test.

It is difficult to determine if stabilization of the practiced pattern constituted a qualitative or quantitative phase transition. To create an attractor other than 0° and 180°, a qualitative transition is necessary when the to be learned pattern is far from either intrinsic attractor. A qualitative shift, or phase transition, occurs due to a non-equilibrium phase transition in the attractor layout. This may occur through the addition of a new attractor through practice or may also result from the loss of an attractor, such as 180°, when practice continues (e.g., Zanone & Kelso, 1992a) or the frequency is increased (e.g., Kelso, 1984). The qualitative shift arises from competition between the intrinsic pattern and the to-be-learned pattern. In contrast, a quantitative shift occurs when there is cooperation from an intrinsic pattern and the to-be-learned pattern (Zanone & Kelso, 1992a). This shift may also occur when an attractor, other than 0^{o} and 180^{o}, moves position in phase space due to practice and is accompanied by a stabilization in performance of the practiced pattern. For example, Zanone and Kelso (1994) reported the gradual shift of an attractor from 90^{o} to 135^{o} as practice at 135^{o} continued. There was not a change in the number of attractors but a shift of the 90^{o} attractor to the new location at 135^{o}. Subjects in Experiment 2 exhibited both types of phase transition. Some added a new attractor through a qualitative transition while others already had a stable attractor other than 0^{o} and 180^{o}. For these subjects, only a quantitative shift was necessary as performance of the to-be-learned pattern stabilized throughout practice. Some subjects, however, were unable to create the phase shift to 45^{o} or 135^{o} and continued performing a pattern close to 90^{o}.

Performance on the last day of practice for all three patterns (45^{o}, 90^{o}, and 135^{o}) does not, by itself, confirm that the patterns were well learned. However, together with the retention data, it is apparent that subjects were able to reproduce the required pattern, indicating permanence of learning. Not only should the intrinsic patterns affect performance of the to-be-learned pattern early in practice but subsequently, the well learned patterns were predicted to influence the intrinsic patterns.

b) Reciprocal Influence of Practiced Patterns on Intrinsic Patterns

The tools of dynamics make it possible to compare initial performance data with ongoing practice data and thus better understand the changes due to learning. Thorough examination of the individual data, however, reveals many individual differences in the learning profiles. This again reinforces the necessity for examination of learning on an individual basis. Group means often are not representative of the members of the group. However, when assessing the effect of a manipulation, it can be useful to compare group means.

Comparison of the intrinsic patterns with the learned pattern allows for an assessment of how the learned pattern was affected by the intrinsic pattern early in learning and how the reciprocal influence might have occurred later in learning.

Early in Practice.

Predictions from theory (Schöner, 1989; Schöner, Zanone, & Kelso, 1992) are unclear as to whether performance would be biased to the stronger or weaker attractor early in practice. Possibly, intended (behavioral) information would override intrinsic influences at the practice frequency (1 Hz) and produced a bias to performing 0° instead of 180° during practice of 90°. Alternatively, competition between 0° and 90° may be greater than between 90° and 180°, because 0° is a stronger attractor. This competition may result in a bias of the error in performing 90° towards the less stable attractor, 180°. The latter explanation seemed to hold true for practice of the 90° pattern. Performance of 45° and 135° early in practice was predicted to be biased toward 90° due to competition from 0° and 180°. Results from Experiment 2 showed all subjects were biased toward the 90° pattern before stabilizing at the to-be-learned pattern. For some, 90° was approximated early in practice and was performed for only a few trials. For others, a search strategy through a number of different patterns, characterized by a high VE, was evident before performance approximated the 90° pattern and was then refined towards the to-be-learned pattern.

From examination of the individual data, it is difficult to assess consistent influences of the intrinsic patterns on the to be learned patterns early in practice of 90°. Some subjects were able to produce the required pattern with little practice. These subjects likely had a general idea of the pattern (without a great deal of stability in performance) already in their repertoire of patterns. For those subjects with a high CE early in practice of 90°, none were biased toward 0°. In general subjects tended to perform a combination of trials near 90°, 180°, and 270°. Lee, Swinnen, and Verschueren (in press) reported a similar "search process toward finding a correct coordination mode" early in practice of the 90° pattern where subjects performed a combination of 0°, 180°, and numerous intermediate phase relations within a trial.

In Experiment 2, many subjects (particularly those in the 135° group) approximated the 90° pattern. This occurred because it appeared to be easier for subjects to produce the 90° pattern as an intermediate step towards the required pattern. The 90° pattern is symmetrical and can be produced by dividing the movement cycle into four equal parts. This allows the subjects to 'break away' from the timing of the intrinsic patterns which requires both limbs to change direction at the same time. This is not to say that all subjects used this strategy, however. Some subjects began approximating the to-be-learned pattern early in practice (without first performing a 90° pattern) while for others it is less clear what strategy they adopted.

The prediction from theory (Schöner, Zanone, & Kelso, 1992) that the 45° pattern will be more difficult to learn due to increased competition from the more stable 0° pattern was not supported in the second experiment. For some subjects, the 45° pattern appeared easier to produce because it required relatively easy modification of the intrinsic pattern 0°. Although there may have been less competition from the 180° pattern for subjects performing the 135° pattern, the ability of subjects to perform 135° seemed to be influenced to a larger degree by other behavioral and intentional information. These influences included (a) biases toward performing with minimum variability regardless of pattern accuracy, and (b) no uniform method for conceptualizing how to perform the task.

Probably the most important finding from the data early in practice is that most subjects had difficulty approximating the to-be-learned pattern. No subject was consistently biased toward 0° early in learning and performance appeared to center around 90°, 180° and 270°. Experiment 2 revealed that competition from the intrinsic patterns biased performance for many subjects toward 90° early in practice.

Later in Practice.

Neither intrinsic pattern showed any permanent loss of stability as accuracy and consistency in performance of 45°, 90°, and 135° stabilized (see Figures 7 & 16). This result would imply that intrinsic attractors have a strong influence on to-be-learned patterns early in practice but the reciprocal effect does not occur once the new pattern is well learned (contrary to Zanone & Kelso, 1992a, 1994).

Competition from 0° and 180° continued to influence performance of the practiced patterns later in practice. Few subjects consistently performed the practiced pattern with a bias toward 0°. For subjects in Experiment 1, the bias was toward 180°. Some subjects in Experiment 2 continued to perform a 90° pattern instead of the to-be-learned pattern.

Neither intrinsic pattern destabilized, but 180° did show an increase in $|CE|$ from pre-test to post-test during practice of 90° (see Figure 6). This demonstrates a temporary effect of practicing 90° on performance of 180°. Stability of 180°, however, was unchanged. A significant effect was not found in Experiment 2, but the trend was similar (see Figure 14). It appears that emergence of the practiced pattern has a weak influence on the accuracy (as measured by $|CE|$) of the intrinsic patterns[4].

Performance of 0° and 180° was also unchanged from the pre-test of the last day of practice to retention, indicating no long term changes in stability or accuracy of the intrinsic attractors (see Figures 6 & 7). As well, retention demonstrated that any change in performance of the intrinsic patterns within the last day of practice was temporary.

Although 45°, 90° and 135° emerged as attractors, they did not appear to influence the stability of the intrinsic patterns. However, if subjects were given terminal feedback on the intrinsic patterns indicating their increased CE, it is possible VE would have increased on the subsequent trial as they attempted to become more accurate. A change in CE could indicate a change in the pattern as it shifts position. For the pattern to maintain position (i.e. a

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4 Examination of individual subject data for Experiments 1 and 2 shows the bias was predominantly towards the practiced pattern (i.e., a negative CE for 180° and a positive CE for 0°).

decrease in CE), VE would increase. To clarify, CE and VE are usually inter-related. A change in VE usually does not occur if the subject is unaware of a drift in CE. Once provided with information about CE, VE may increase in an effort to correct the CE.

Contrary to empirical data (Zanone & Kelso, 1992a, 1994) and theoretical predictions (Schöner, 1989; Schöner, Zanone, & Kelso, 1992), subjects seemed to continue to be influenced by the intrinsic patterns. Though well learned, the practice patterns had little or no effect on the intrinsic patterns.

The present results appear to support the work of Lee, Swinnen, and Verschueren (in press) in that no destabilization of the intrinsic patterns was discovered. Interestingly, there was some evidence for an increase in $|CE|$ (particularly for 180°) within each day of practice (also seen on the first day of practice in Lee, Swinnen, & Verschueren, in press). It may be that subjects maintained the same stability for the intrinsic patterns at the end of each practice session, but their accuracy was biased toward the practiced pattern. This effect was greatest for the 45° group performing the 0° pattern (see Figure 14).

<u>c) Alternative Explanations</u>

So far, the performance of subjects has been explained in terms of the reciprocal influence of intrinsic patterns and the practiced patterns. The present results may also be accounted for, in part, by examining the influence of behavioral information, the method of sampling intrinsic patterns, and the effect of a hand preference in performing the to-be-learned patterns. For example, intersubject differences may be due to the emphasis the subjects puts on accuracy as opposed to stability and the preference for subjects to lead with the left hand and not the right.

Trading off Accuracy and Stability.

The visual feedback seemed to motivate some subjects to perform the pattern with an emphasis on reduced variability even with a trade-off for accuracy. Subjects in both experiments (particularly those performing 135°) seemed satisfied in performing the required pattern with a low VE and relatively high CE. It would appear that behavioral information, mapped onto the attractor layout, influenced production of the pattern such that a pattern other than the to-be-learned pattern was preferred because change would require an increase in VE. An increase in VE would produce a trace with less consistency and this was not desired by some subjects. Although no reports were taken from the subjects, it was evident that each trial of increased VE was followed by a trial with decreased VE and increased CE (biased toward 90°). The terminal visual feedback, as anecdotally reported by some subjects, motivated them to perform a consistent trace and accuracy of the trace over the goal template often seemed a secondary goal.

Most notably, some subjects in Experiment 2 became comfortable in performing the 90° pattern and were unwilling to increase their variability in order to effect a change to approximate the 45° or 135° pattern. Behavioral intentions appeared to inhibit subjects from initiating change by increasing variability.

Handedness.

Most subjects had a negative bias in performing 180° and a positive bias for the 0° pattern. If the right hand was leading the left when performing these patterns then both these biases would exist. Carson, Byblow, and Goodman (1994) demonstrated that the left hand adjusts its phase relation when a bimanual switch is observed from 180° to 0° as the cycling frequency is increased. More recent work (Byblow, Carson, & Goodman, 1994) has further shown support for the right hand to be dominant (more stable limb) when the movements are paced by an auditory metronome.

Handedness may also have an effect on performing patterns other than 0° and 180°. All subjects were right handed and likely found it less difficult to consider performing patterns with reference to the right limb. In addition, the instructions given to subjects were all with reference to the right hand at the middle position and the left hand at the relative position depending on the intended pattern.

The task imposed on the subjects required that the right hand lead the left. However, some subjects preferred to perform the required pattern with the left hand leading the right. In each case, (either for 45°, 90°, or 135°) this produced a pattern 180° opposite from what was required and the experimenter notified the subject at the end of each trial that it had occurred. However, it does raise the issue of the effect of preference for a lead hand when performing some of the patterns. Presumably, each subject has a preference for leading with one hand or the other. While all subjects seemed able to lead with the right hand, as instructed, some showed a distinct preference for a left lead early in practice. For those subjects, CE was high, not because the timing between the two limbs was inappropriate, but because the left hand was leading in performance of the task. VE was also high as the subjects often switched between left- and right-hand lead patterns within each trial.

It would be interesting to see how the results would change if the lead hand was not specified. Presumably, subjects who performed a 315° pattern instead of 45° (as 315° is the symmetric opposite of 45°) would likely have a performance bias for the in-phase pattern toward 315° (negative CE) and not 45° (positive CE). The preference for a left hand lead by right handed subjects is not uncommon. Right-handed readers may have the experience of playing some sports 'left-handed' such as golf, baseball, or hockey.

Method for Sampling the Attractor Layout.

Zanone and Kelso (1994) showed a destabilization of the 180° concurrent with the emergence of 90° as an attractor. In the present experiment, and in Lee, Swinnen, and Verschueren (in press), a temporary but not long term destabilization of 180° was found. This contradictory result may not reflect a difference in the attractor layout, but instead a difference in examining performance of the different patterns. Zanone and Kelso (1994) scanned the entire attractor layout by pacing subjects with two visual metronomes at relative phases in 15° increments starting at 0°. Because 90° became an attractor, patterns near 90° were performed with a bias to 90°. This effect occurred for a number of patterns performed during scanning after 90° (e.g., 105° & 120°). Only the last pattern before 180° (i.e., 165°) was biased to 180°. It is conceivable that the opposite effect would have been observed if the scanning trials started at 180° and worked to 0°. It may be that patterns are not biased to 180° merely because 90° was the most recently performed pattern that was an attractor. It is possible that perceptual carry-over effects confounded Zanone and Kelso's (1992a) results and 0° may have appeared to have destabilized if scanning was done in the reverse order. The protocol in the present experiment was modelled from Lee, Swinnen, and Verschueren (in press) in examining only the patterns of interest. Examining 0° and 180° 'discretely' showed no destabilization of either intrinsic pattern.

Ability to Conceptualize Performance of the to-be-learned Pattern.

Differences between subjects and between practice groups in Experiment 2 may also be due to how subjects conceptualized performance of the to-be-learned pattern. To perform the 45° task, subjects would often adapt the 0° pattern by imposing a lead of one-eighth of a cycle for the right hand. It would be plausible that the 0° pattern would subsequently be affected and the right hand would slightly lead the left creating a positive CE. The same might not be the case for 135°. The 135° pattern can be produced either by altering the 180° pattern by one-eighth of a cycle or by changing the in-phase pattern by three-eighths of a cycle. Although the end result would be the same (production of a 135° pattern) the way in which subjects conceptualized the task may have influenced how it affected the intrinsic patterns.

In addition, three subjects in the 135° group (and two in the 45° group) preferred to produce a 90° pattern. Results from the first experiment revealed that subjects performing a 90° pattern lose accuracy of the 180° pattern within each day but improve across days. No subject, however, demonstrated a distinct or significant loss of stability of the intrinsic patterns during practice of the to-be-learned pattern. It is possible that, without feedback, subjects attempted to perform the pattern with as much stability (consistency) as possible and were unaware of their loss of accuracy. If the subjects had been presented with feedback, it is conceivable that they would have attempted to decrease their CE and consequently increased their VE.

d) Summary and Future Directions

Two distinct questions were asked in the present experiments. First, does learning a pattern equidistant from both attractors influence either of these intrinsic patterns? Second, in learning 45° and 135° patterns, what are the differences in learning the patterns, and are these differences reflected in the intrinsic patterns?

Theory predicts that the anti-phase pattern will lose stability in performance when another pattern becomes well learned (Schöner, 1989; Schöner, Zanone & Kelso, 1992). Although it is not possible to qualitatively state that the 45°, 90°, and 135° patterns became well learned, it is clear that the VE and particularly the |CE| levelled off at values near those of the intrinsic patterns. These consistent values would suggest that the new patterns were well learned and became part of the attractor layout. This conclusion is reinforced by the retention data. In contrast to earlier work by Zanone and Kelso (1992a, 1994), subjects were able to learn a new pattern without sacrificing the ability to perform existing patterns. Based on the present findings, 45°, 90°, and 135° appeared as new attractors without concurrent destabilization of an intrinsic attractor.

As discussed in part (a) of the general discussion, competition was observed, particularly in practice of the 90° pattern as it was biased away from the stronger attractor, 0°. Both qualitative and quantitative phase transitions were observed, as predicted from theory (Schöner, 1989). To establish a pattern other than 0° and 180°, subjects required a qualitative phase transition (or non-equilibrium phase transition). Once created, a quantitative transition occurred as performance of the pattern became more accurate and stable.

The first experiment demonstrated that with six days of practice, a plateau in performance (and presumably learning) occurred. For the second experiment, only four days of practiced were used. It is more difficult to assess if a plateau occurred but the values, particularly for VE, are very similar for 45° and 135° groups when compared to days 4, 5, and 6 for the 90° group in Experiment 1. While it is not certain a plateau was reached, it seems apparent that the practiced patterns became well learned. This leads to the conclusion that neither intrinsic pattern destabilized with the addition of the new pattern. Based on the present findings, and anecdotal reports from subjects, it is likely, particularly in those learning 45° or 135°, that the repertoire of patterns that can be maintained is extremely large if not endless. While this may be specific to the present experimental setup, it would be possible for subjects to perform 90° and likely a number of other patterns with relative accuracy and stability. In particular, subjects would likely be able to perform those patterns 'between' 90° and 45°, or 135° and 180°, or 0° and 45°. On the time course of learning, it may be that a few trials are needed to refine the pattern but certainly not the hundreds (or thousands) of cycles initially required to learn a pattern different from 0° and 180°.

Based on the present findings, there are a number of different avenues for future research: (a) feedback and shifts in CE and VE, (b) handedness and anchoring effects in learning, (c) transfer after learning a pattern other than 0° and 180°, and (d) effect of information on learning a new pattern.

Practice of a new pattern biased performance of the 180° pattern toward the new pattern. However, stability went unchanged. If subjects were given feedback about the error, they may increase VE in an attempt to reduce VE. Thus, if the same practice schedule was used, but feedback was given for the intrinsic patterns, an increase in VE (an indicator of pattern destabilization) may be observed.

Some subjects preferred to perform the to-be-learned pattern with the left hand leading the right. For these subjects, the large CE and VE scores likely would not have been observed if a lead hand was not specified. However, it does suggest a preference by subjects in performing patterns other than 0° and 180°. Conservation of symmetry may not be equal as suggested by Zanone and Kelso (1994).

Based specifically on results from Experiment 2, learning rate for 45° or 135° should be compared for two groups. One group having already practiced 90° and the other only having 0° and 180° in their attractor layout. Subjects who already have an attractor other than 0° and 180° should learn the new pattern much faster, through a quantitative shift (e.g., Zanone & Kelso, 1994). The group without a third attractor would have to go through a qualitative shift first (e.g., Zanone & Kelso, 1992). It is predicted that the qualitative phase transition will take longer on the learning time scale.

A second focus should be on the role of information in production of the required patterns. In particular, vision of the hands (or more generally, focus of attention) may influence rate of learning. If subjects are able to observe the movement of their hands, attention is focussed medially. For patterns (such as 135°) where the hands are never near each other medially, it may be an advantage for subjects to use vision in performing a 45^{o} pattern where both hands are close to the 'in' position each cycle. This influence may be greater for bimanual movements with large amplitudes where vision plays a larger role than in finer movements such as bimanual coordination of the fingers or wrists.

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Table 1

Summary of sequence of practice and retention trials for Experiment 1

Practice Sessions[1]

# of Trials	Pattern	Feedback
2	0°	none
2	180°	none
2	90°	none
15	90°	terminal every trial, augmented every 5th trial
15	90°	terminal every trial, augmented every 5th trial
15	90°	terminal every trial, augmented every 5th trial
2	0°	none
2	180°	none
55 - Total		

Retention Session[2]

# of Trials	Pattern	Feedback
2	0°	none
2	180°	none
2	90°	none
6 - Total		

---

1 performed on 6 separate days

2 performed 4 weeks after the last practice session

Table 2

Summary of sequence of practice and retention trials for Experiment 2

Practice Sessions[1]

# of Trials	Pattern	Feedback
2	0°	none
2	180°	none
2	45° or 135°	none
15	45° or 135°	terminal every trial, augmented every 5th trial
2	0°	none
2	180°	none
15	45° or 135°	terminal every trial, augmented every 5th trial
2	0°	none
2	180°	none
15	45° or 135°	terminal every trial, augmented every 5th trial
2	0°	none
2	180°	none
63 - Total		

Retention Session[2]

# of Trials	Pattern	Feedback
2	0°	none
2	180°	none
2	45° or 135°	none
6 - Total		

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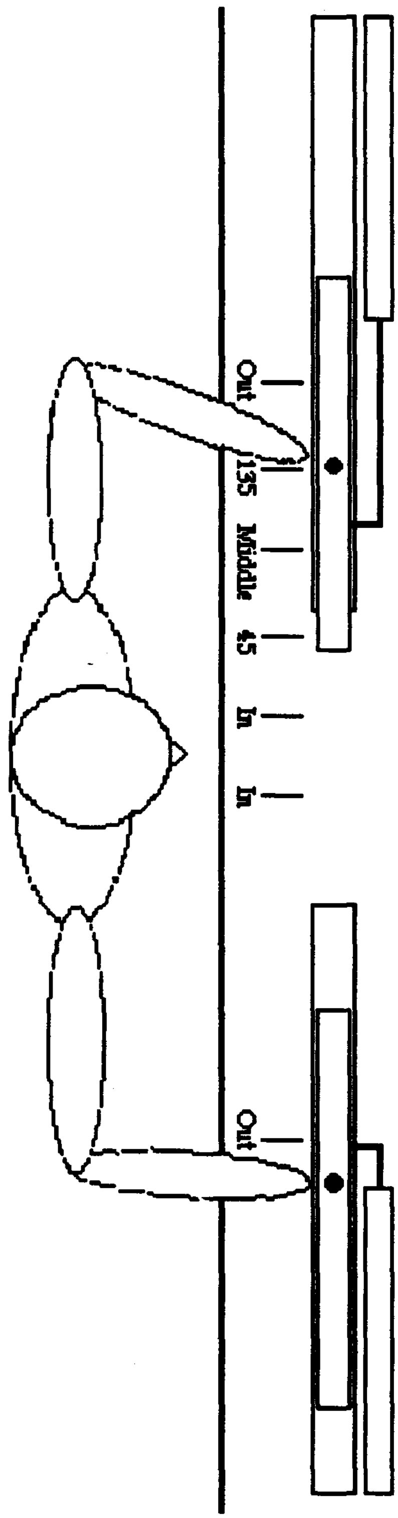
1 performed on 4 separate days

2 performed 4 weeks after the last practice session

Figure Captions

Figure Page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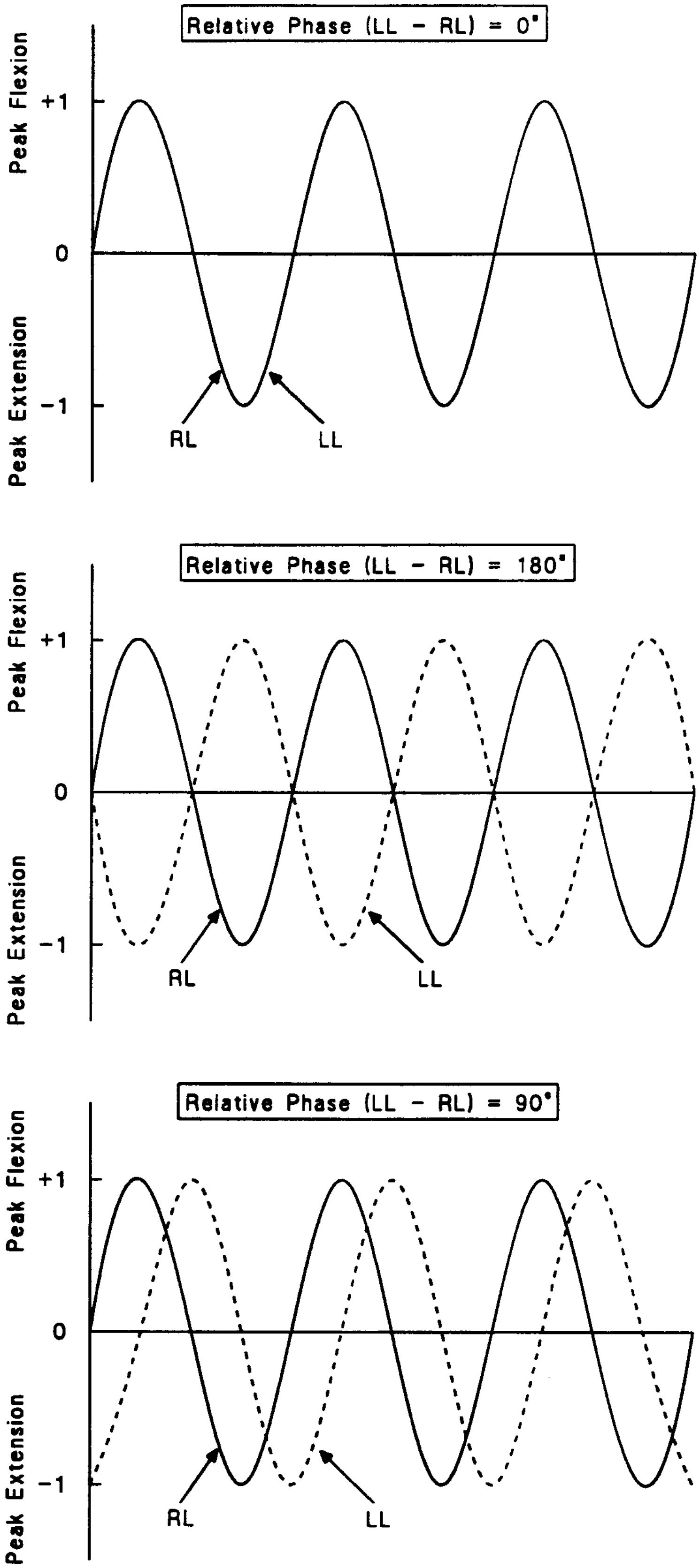
Middle
45
In
In
Out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Peak Extension
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RL
LL
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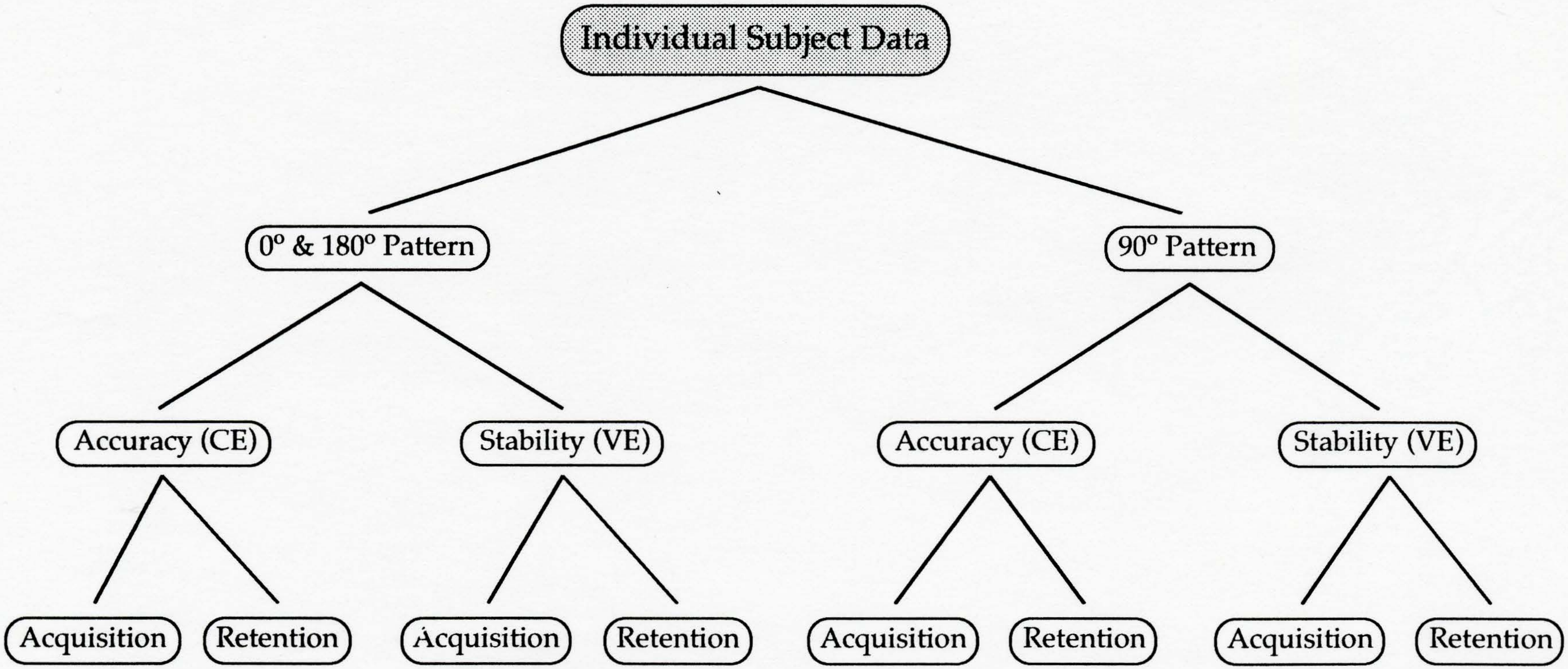
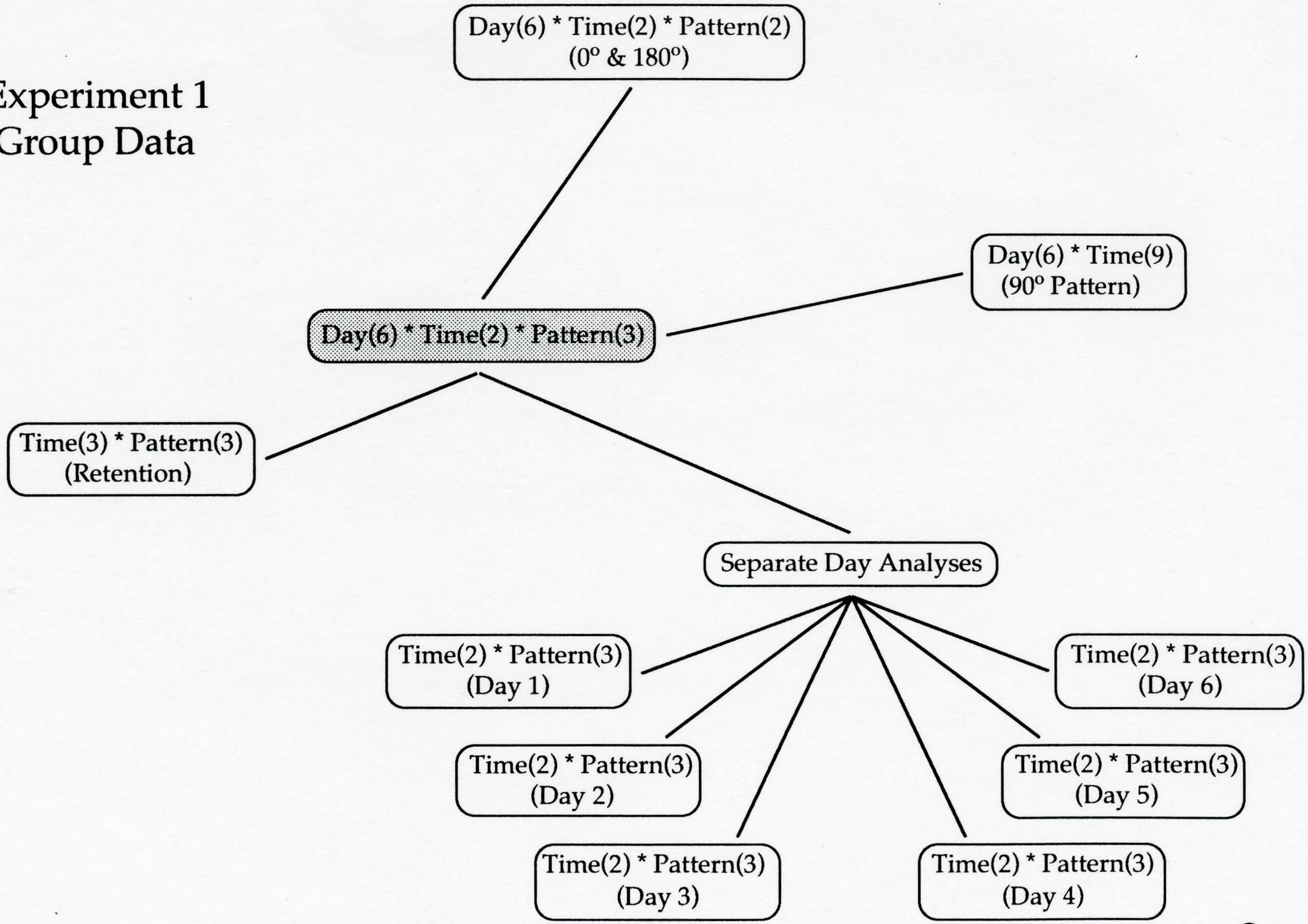
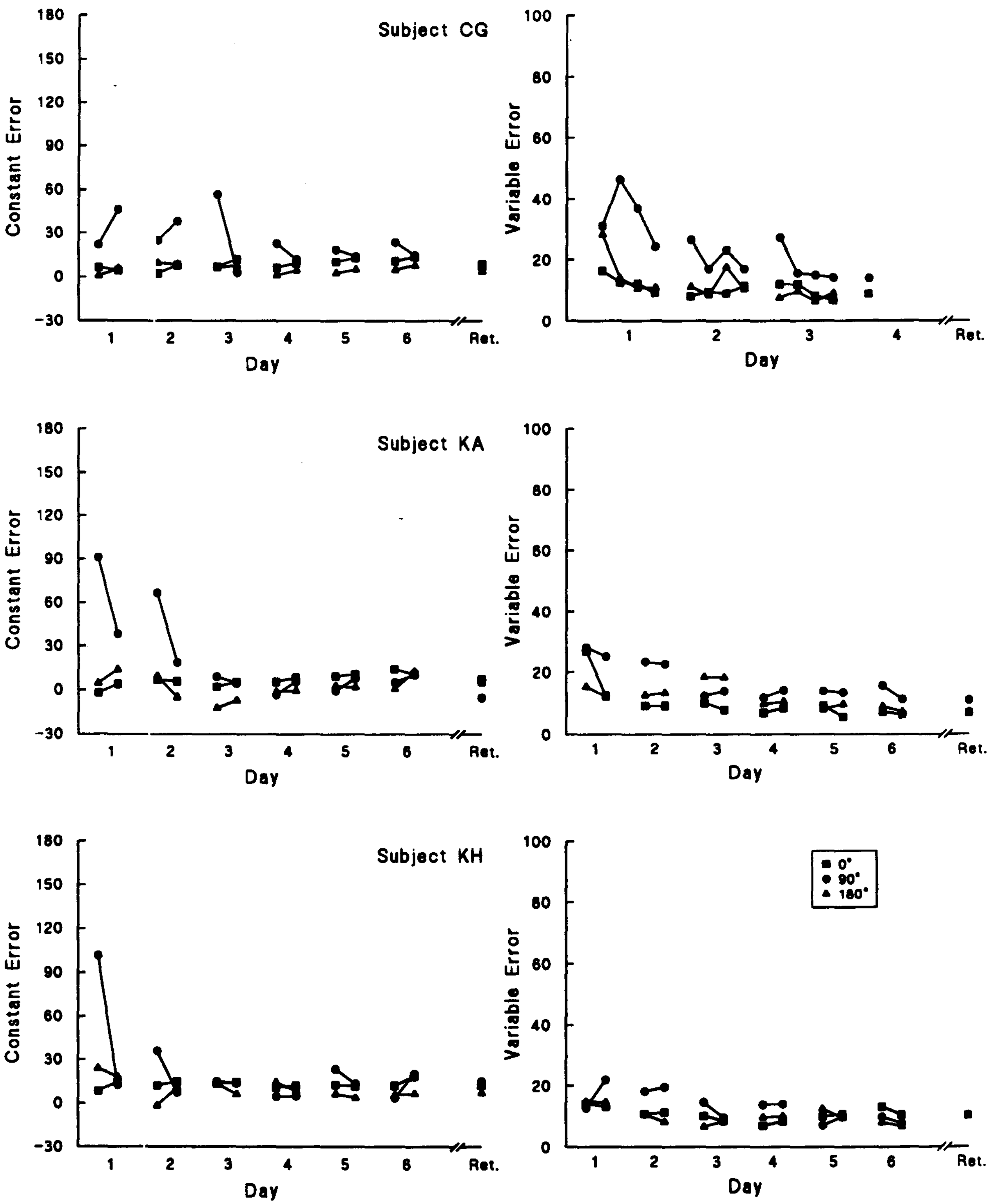
Peak Extension
−1
RL
LL


Individual Subject Data
0° & 180° Pattern
90° Pattern
Accuracy (CE)
Stability (VE)
Accuracy (CE)
Stability (VE)
Acquisition
Retention
Acquisition
Retention
Acquisition
Retention
Acquisition
Retention

Experiment 1
Group Data

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Variable Error
Day
Ret.
Subject KA
Constant Error
Variable Error
Day
Ret.
Subject KH
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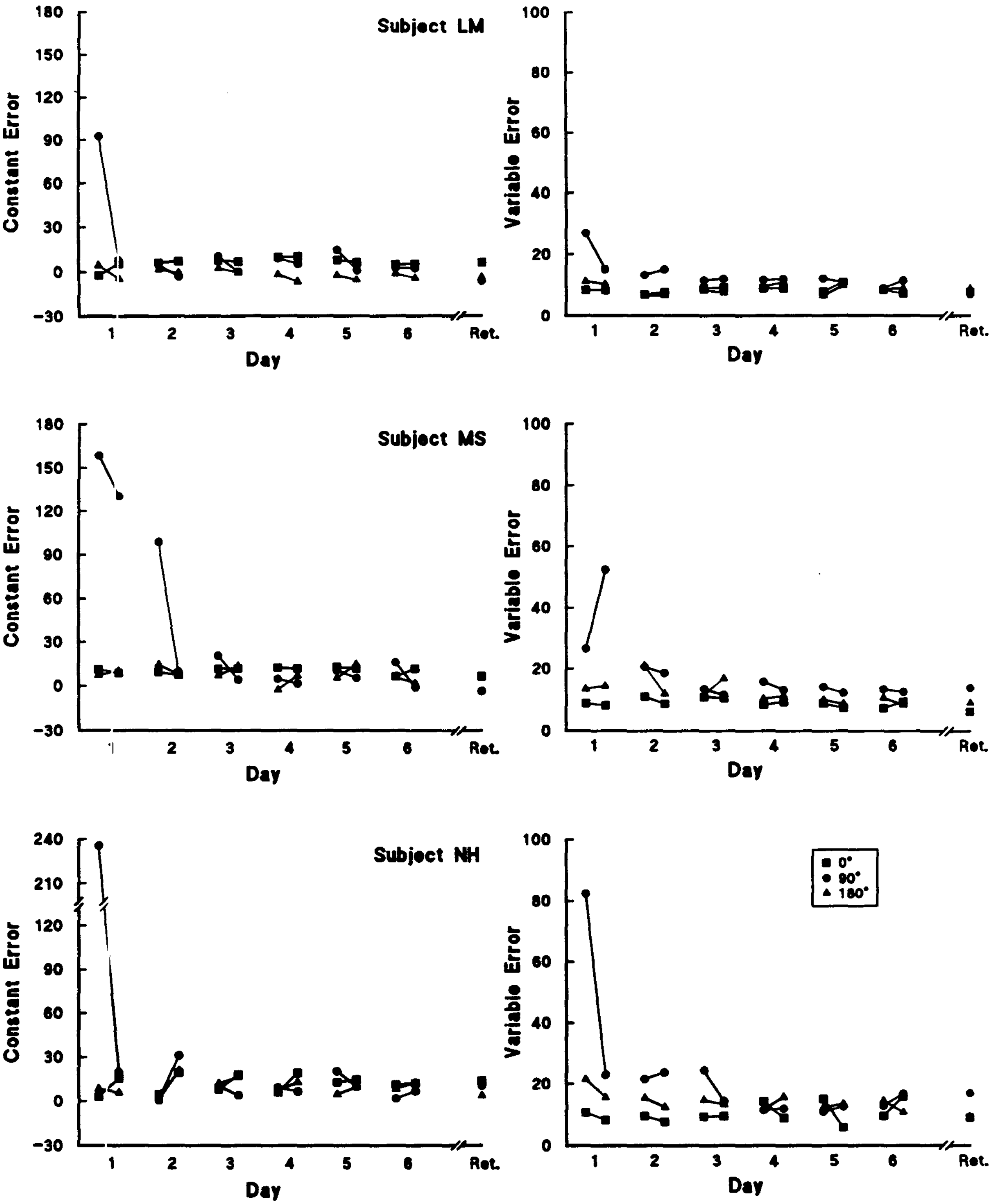
Variable Error
Day
Ret.
0°
90°
180°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Subject MS
Subject NH
Constant Error
Variable Error
Day
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2
3
4
5
6
Ret.
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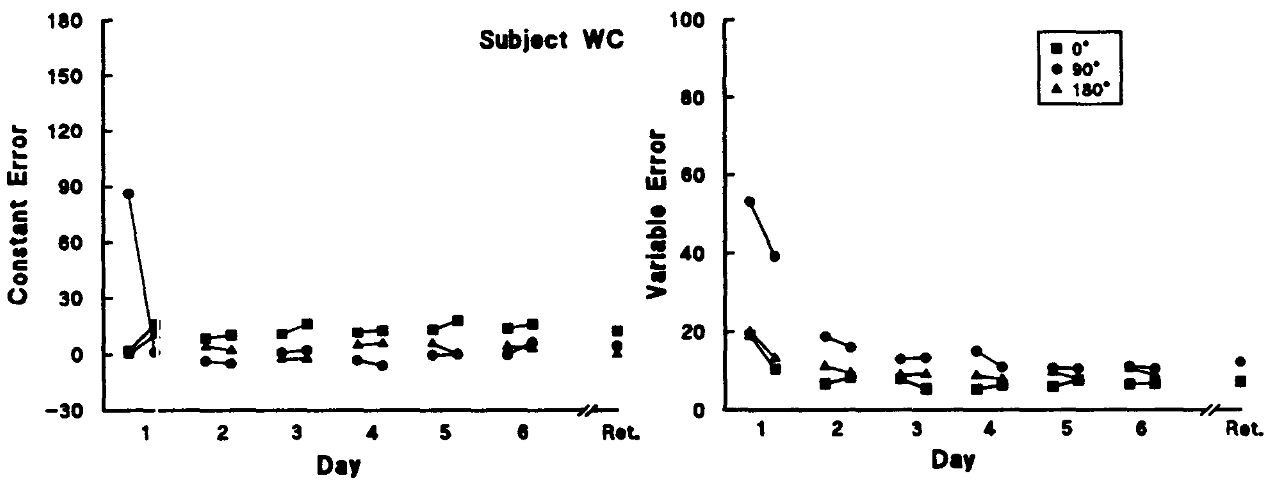
90°
180°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120
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60
30
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3
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6
Ret.
Day
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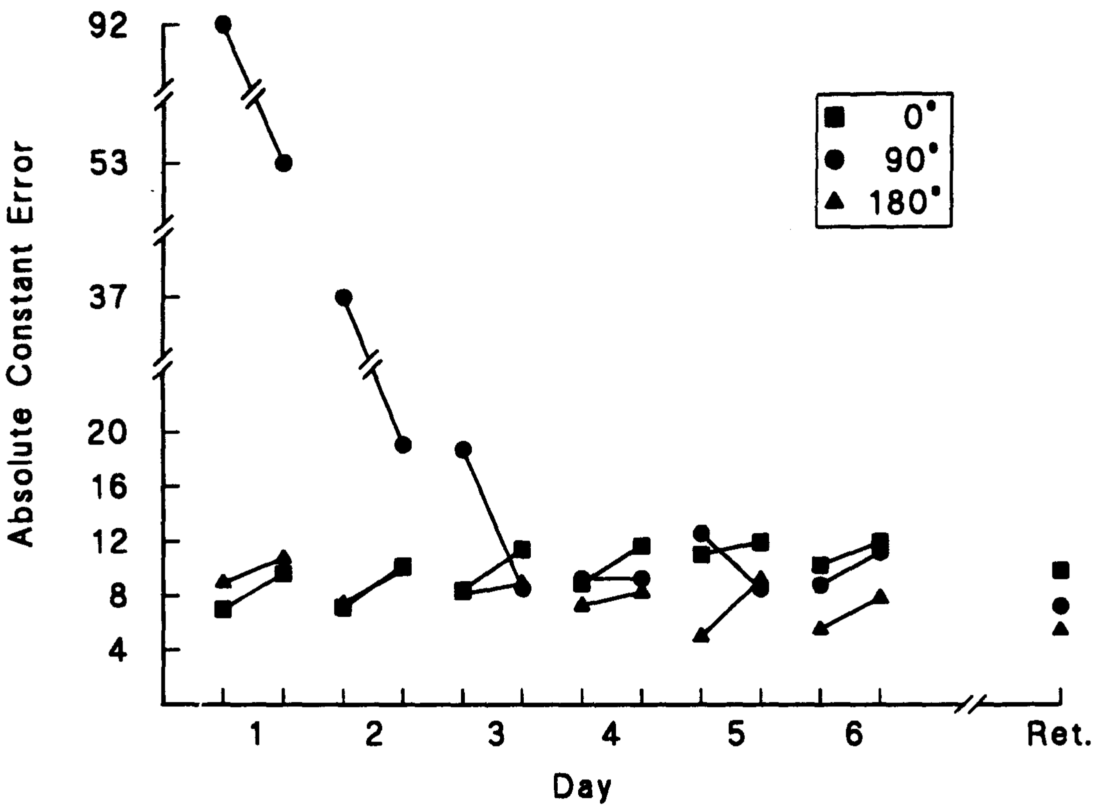
0
0°
90°
180°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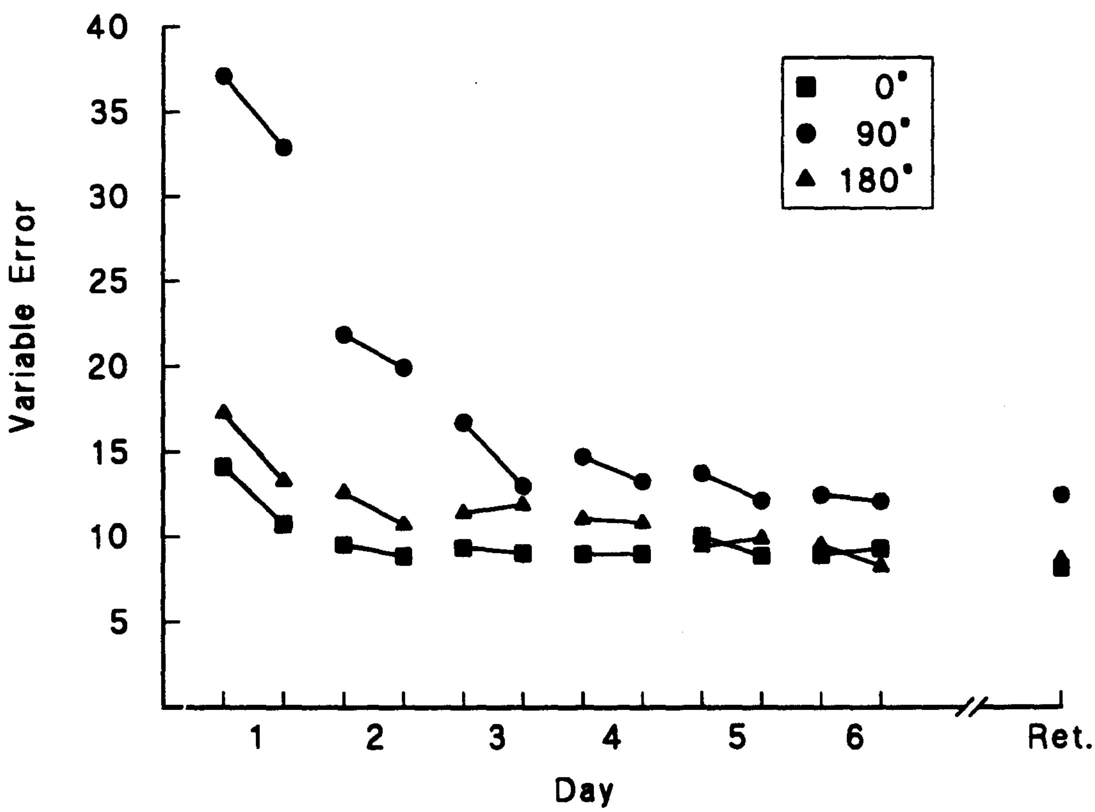
16
12
8
4
0°
90°
180°
1
2
3
4
5
6
Ret.
Day


Variable Error
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25
20
15
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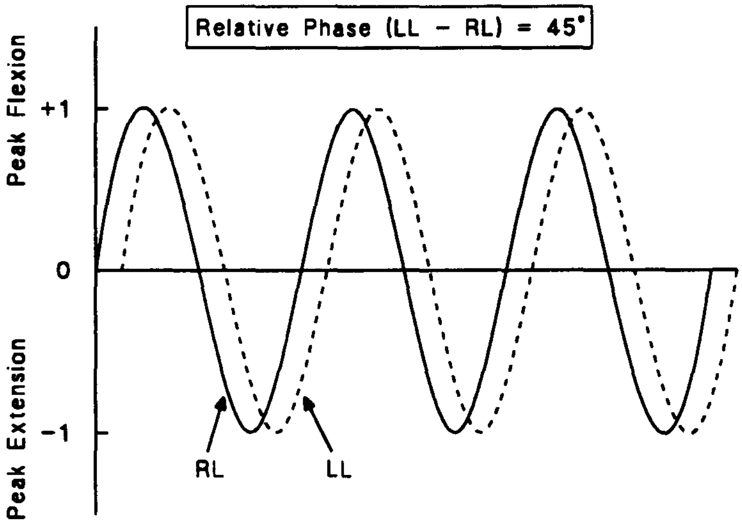
0°
90°
180°
1
2
3
4
5
6
Ret.
Day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Peak Flexion
+1
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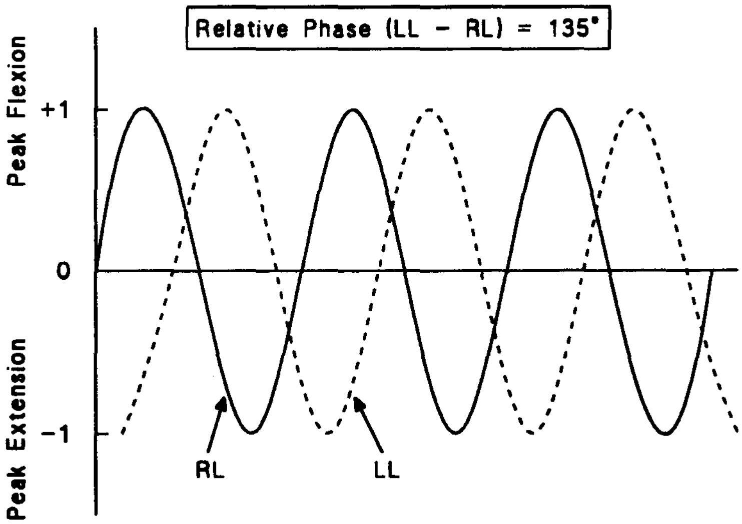
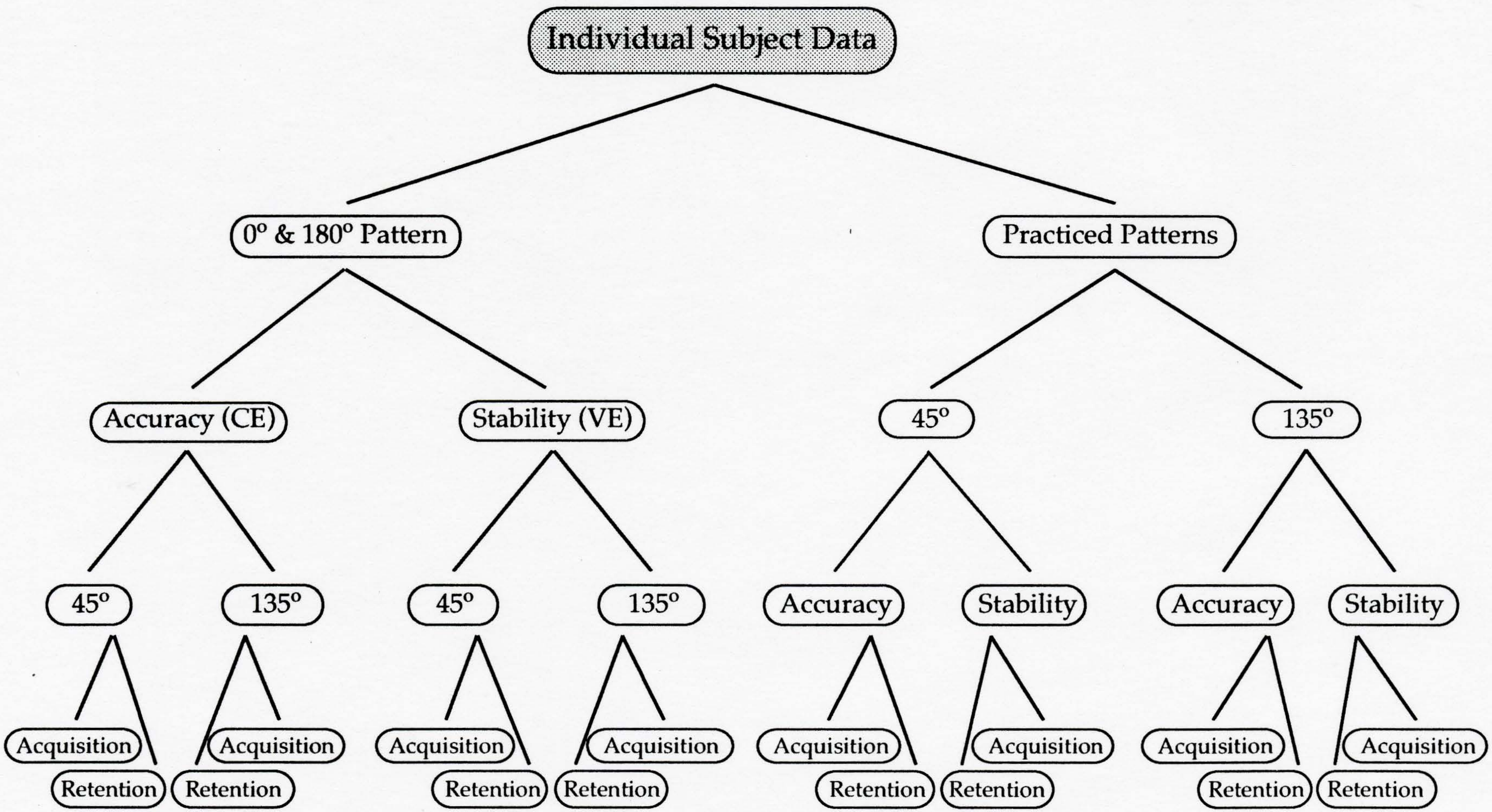
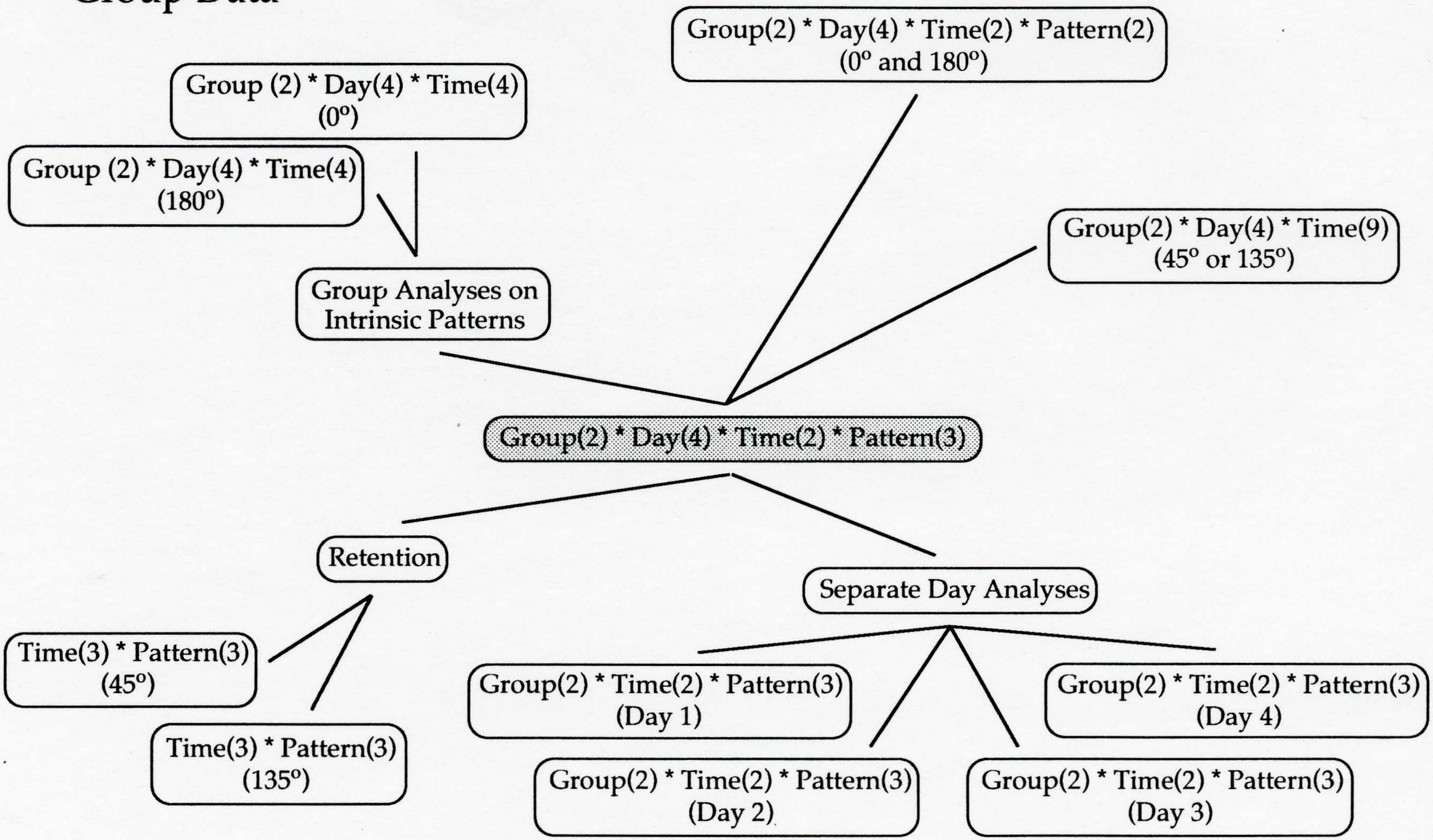
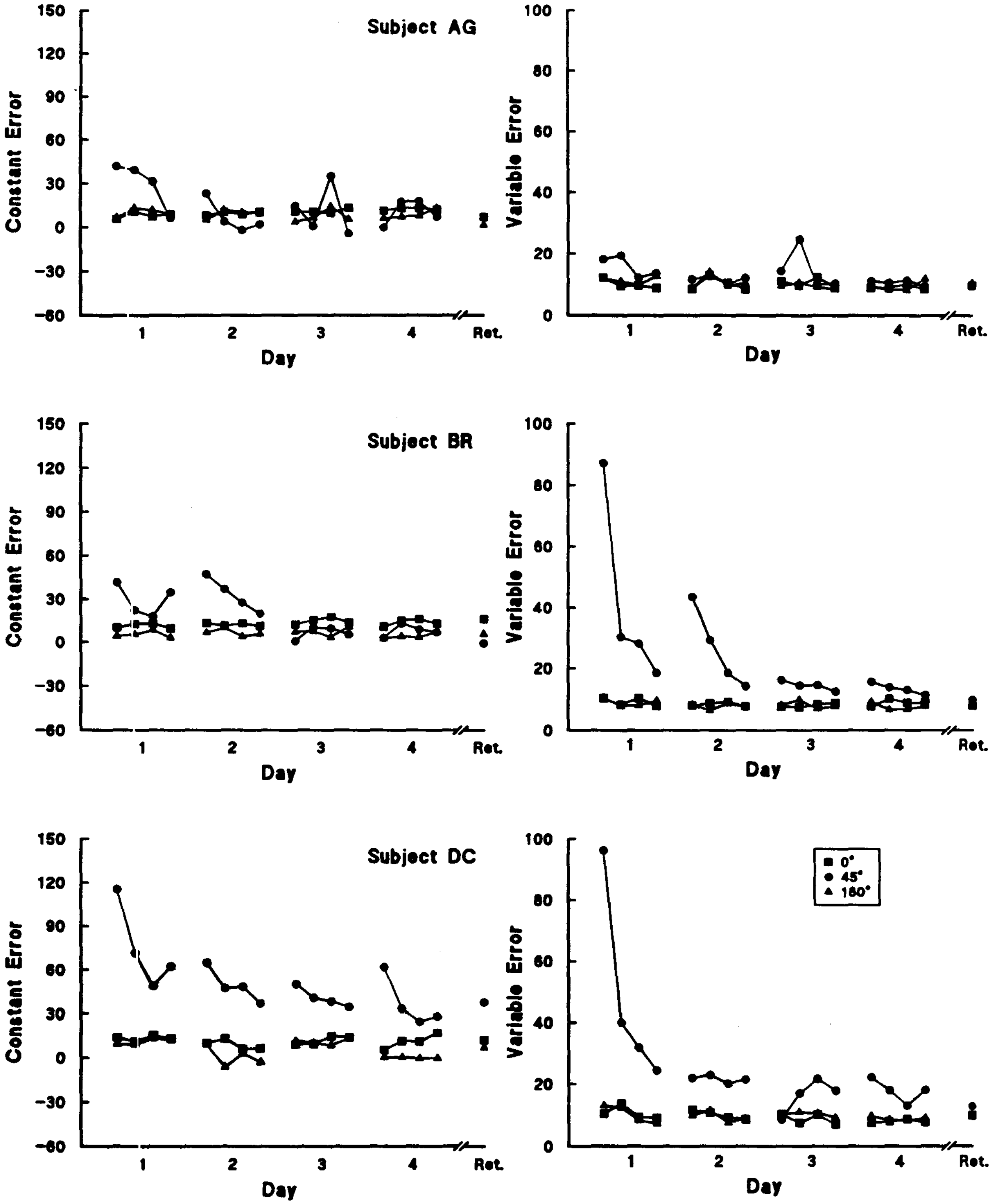
RL
LL

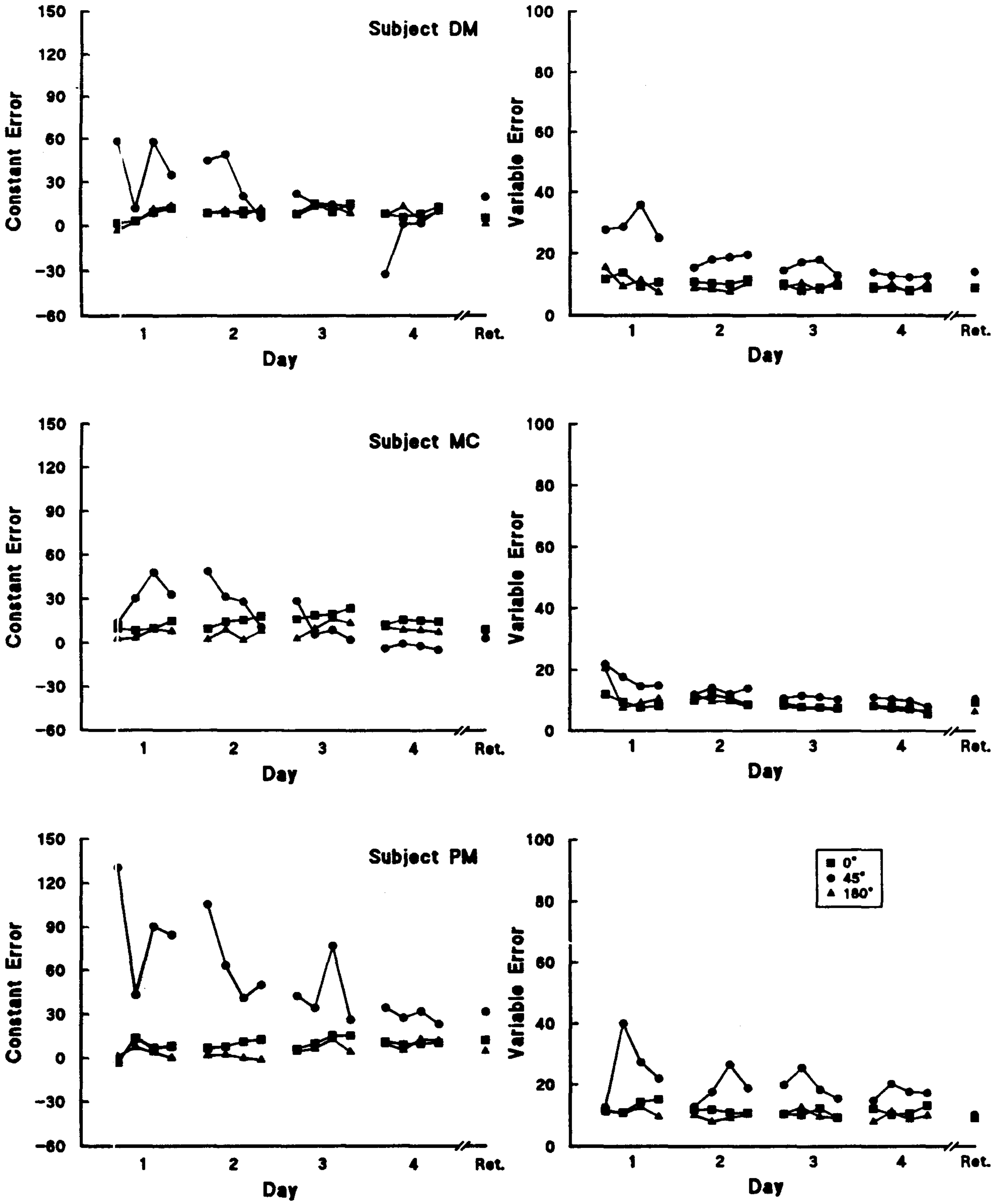

Relative Phase (LL - RL) = 135°
Peak Flexion
+1
0
Peak Extension
-1
RL
LL

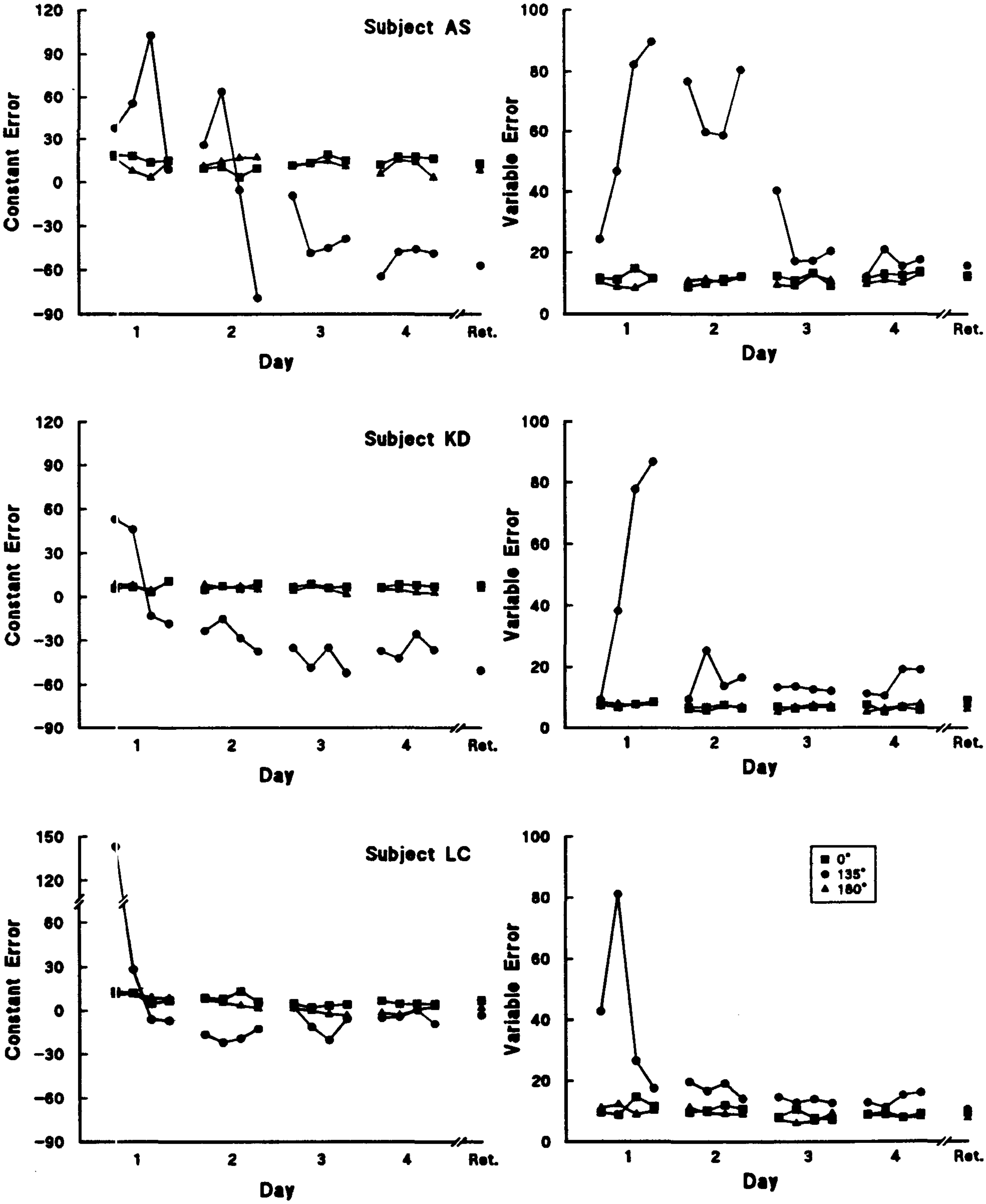

Individual Subject Data
0° & 180° Pattern
Practiced Patterns
Accuracy (CE)
Stability (VE)
45°
135°
45°
135°
45°
135°
Accuracy
Stability
Accuracy
Stability
Acquisition
Retention
Acquisition
Retention
Acquisition
Retention
Acquisition
Retention
Acquisition
Retention
Acquisition
Retention
Acquisition
Retention
Acquisition
Retention

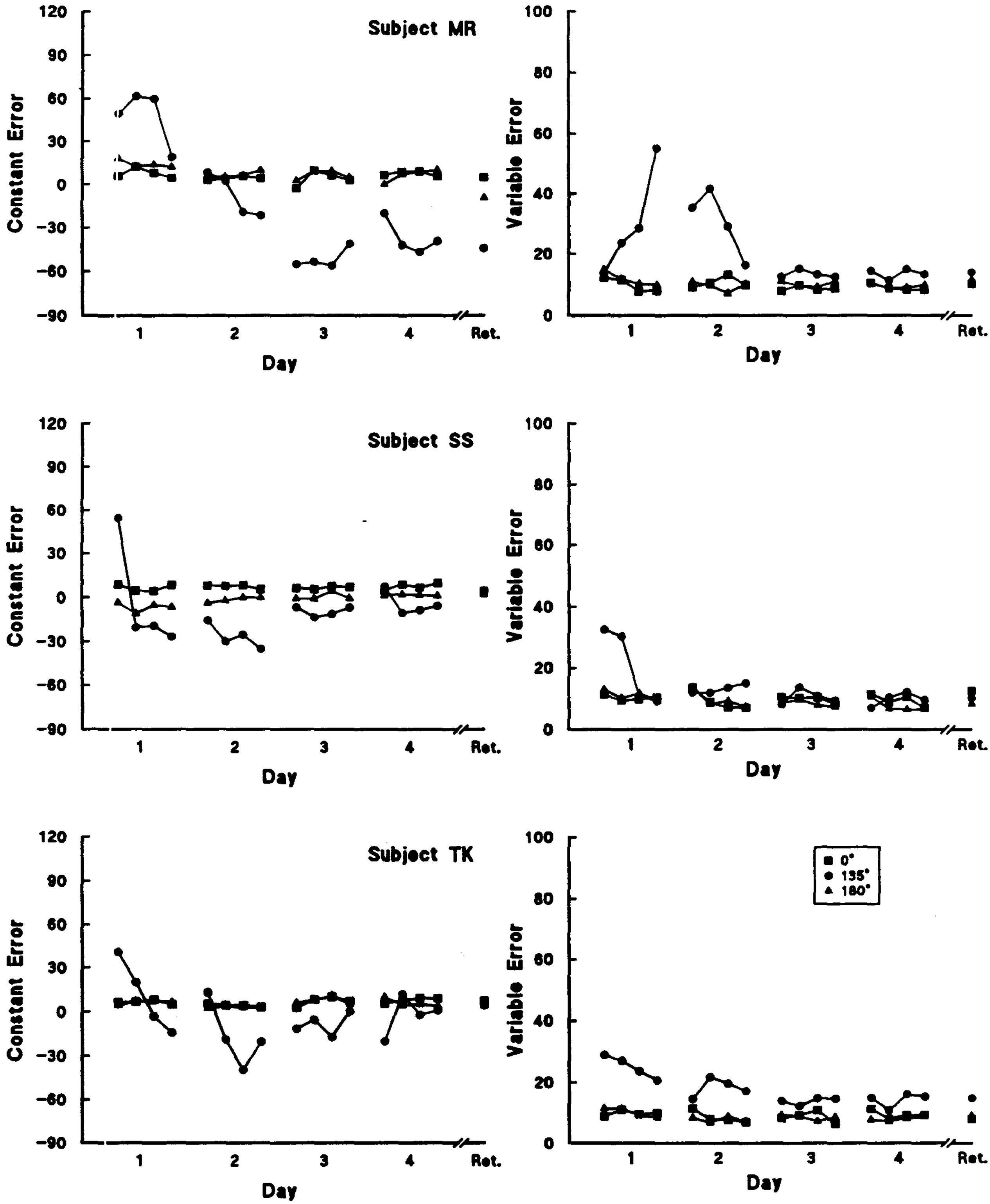
Experiment 2
Group Data

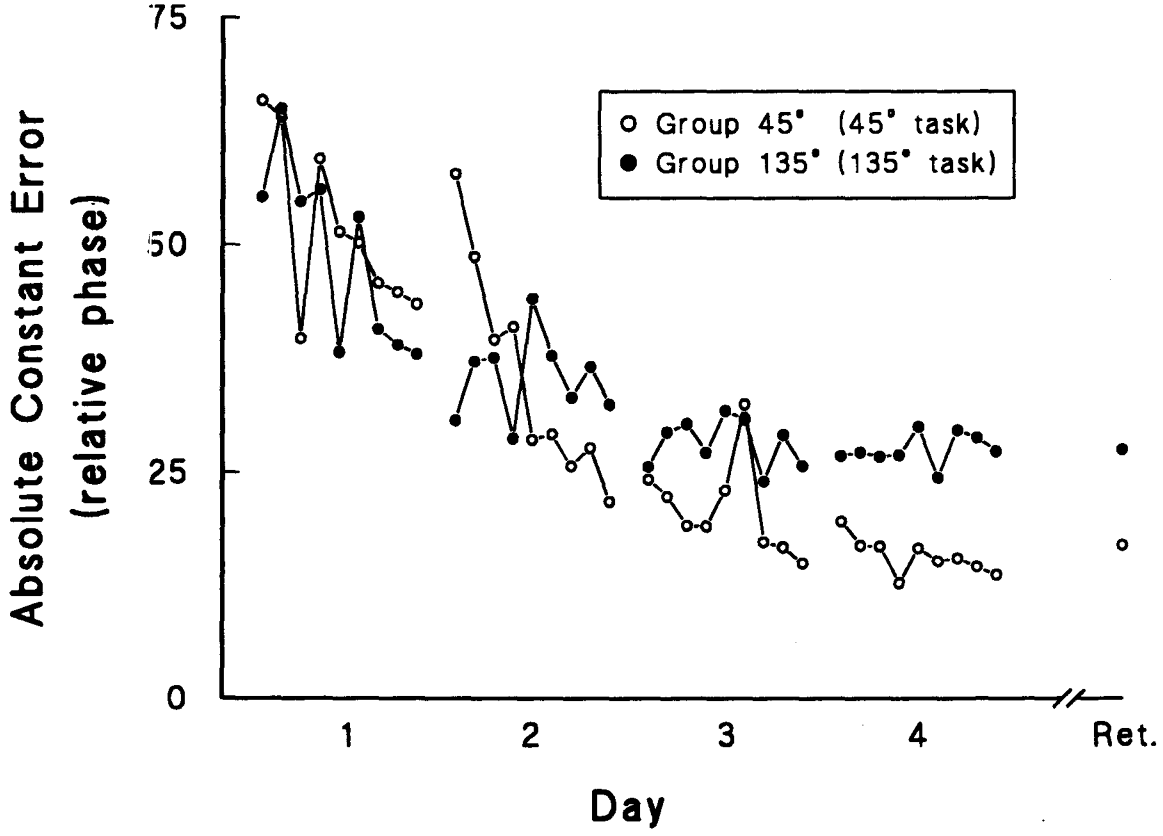


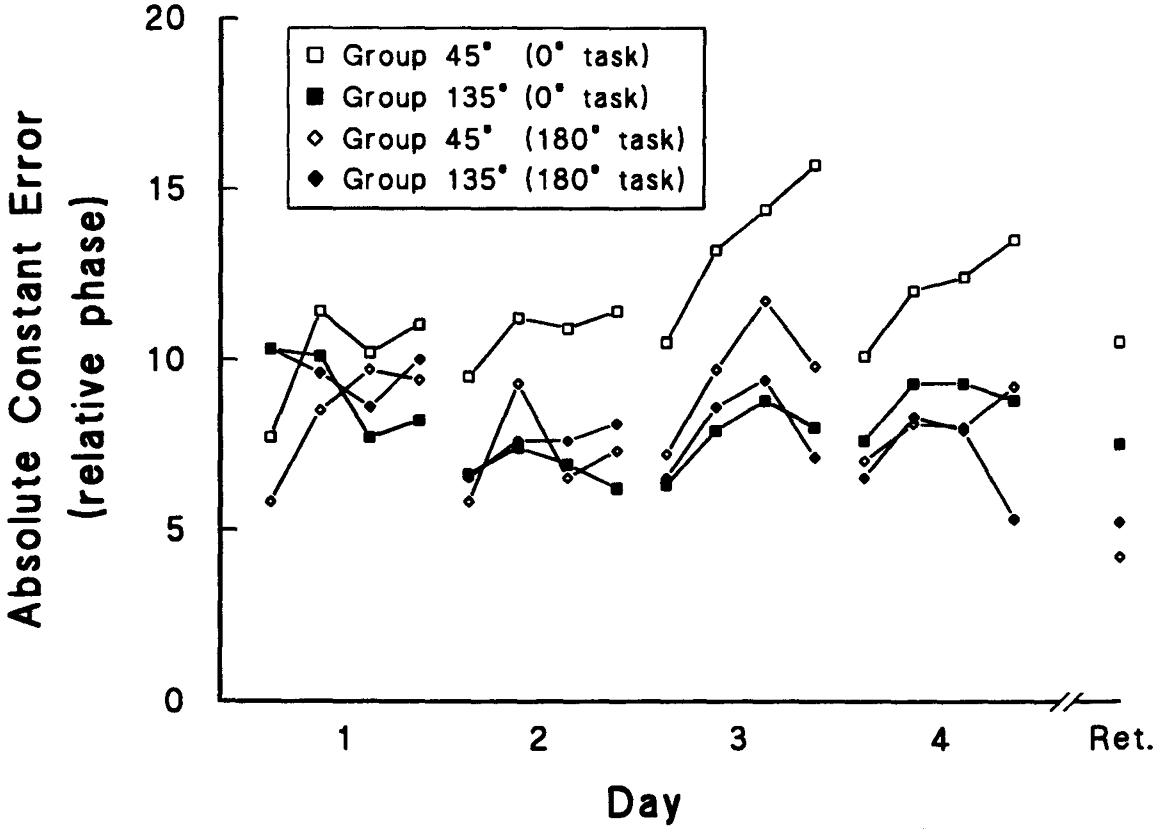

Subject AG
Subject BR
Subject DC
Constant Error
Variable Error
Day
Ret.
■ 0°
● 45°
▲ 180°

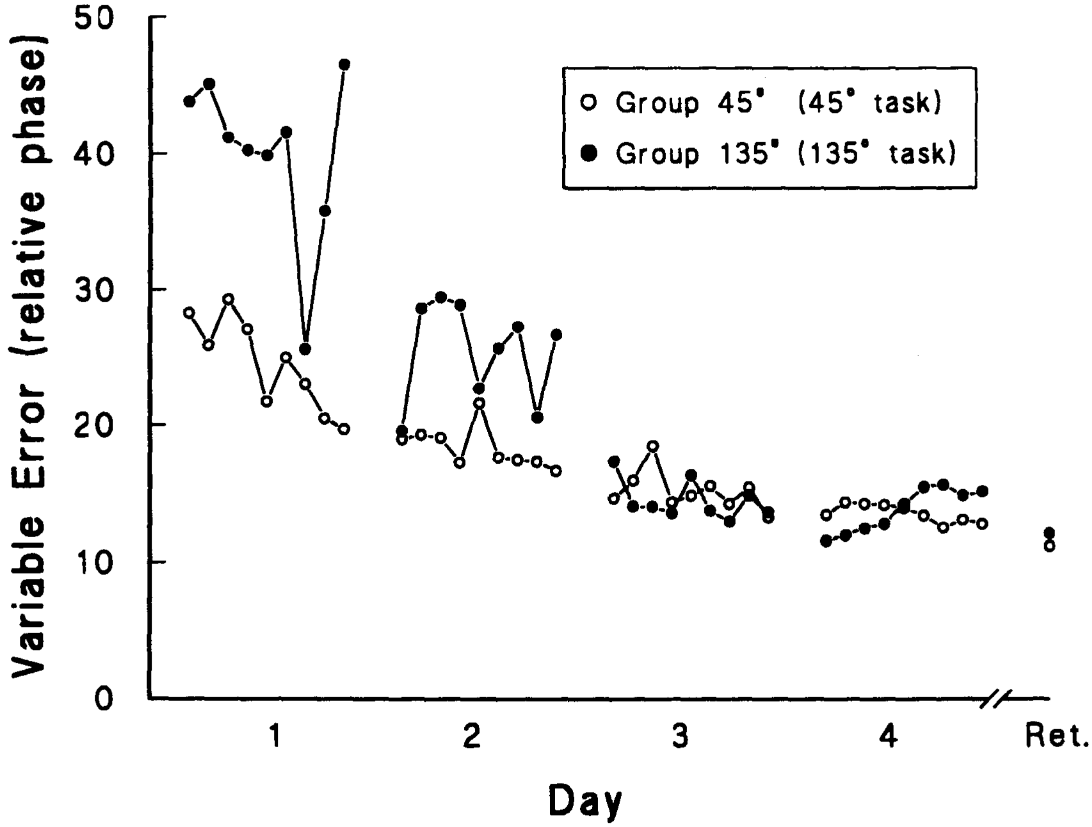

Subject DM
Subject MC
Subject PM
Constant Error
Variable Error
Day
1
2
3
4
Ret.
■ 0°
● 45°
▲ 180°

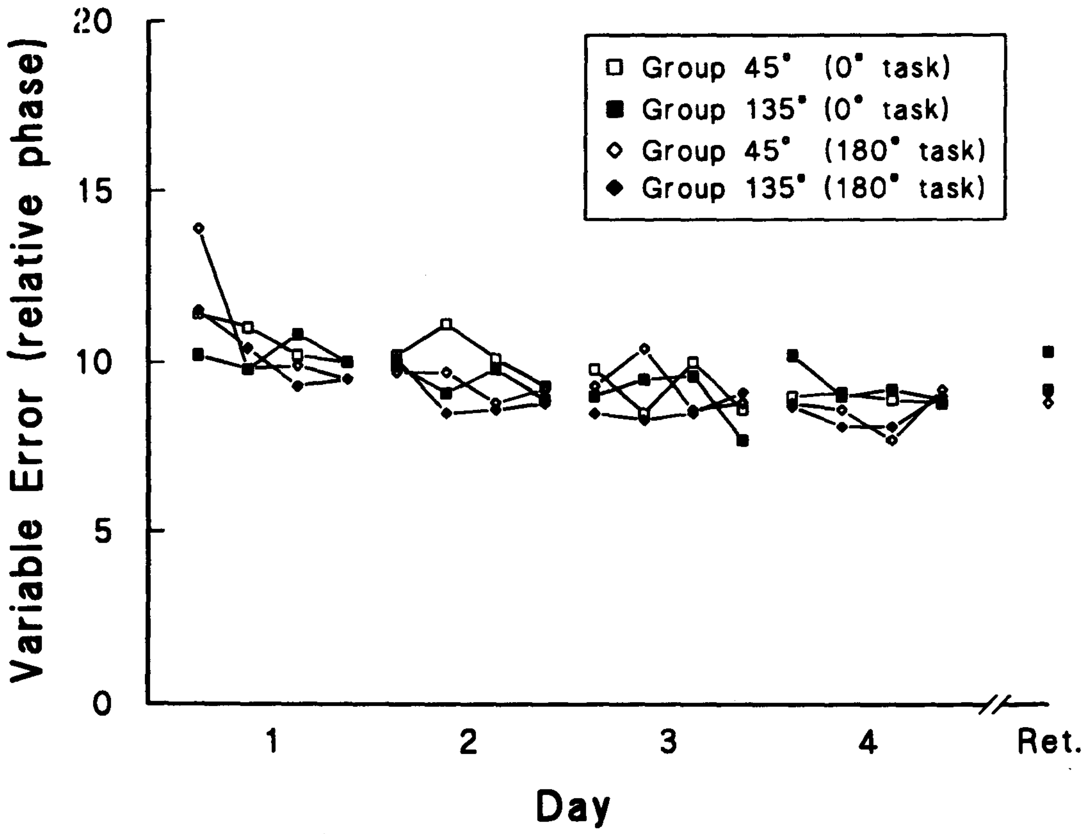

Subject AS
Subject KD
Subject LC
Constant Error
Variable Error
Day
1
2
3
4
Ret.
■ 0°
● 135°
▲ 180°


Subject MR
Constant Error
Variable Error
Day
1
2
3
4
Ret.
Subject SS
Constant Error
Variable Error
Day
Subject TK
Constant Error
Variable Error
Day
0°
135°
180°


75
50
25
0
Absolute Constant Error
(relative phase)
Group 45° (45° task)
Group 135° (135° task)
1
2
3
4
Ret.
Day


20
15
10
5
0
Absolute Constant Error
(relative phase)
Group 45° (0° task)
Group 135° (0° task)
Group 45° (180° task)
Group 135° (180° task)
1
2
3
4
Ret.
Day


Variable Error (relative phase)
50
40
30
20
10
0
Group 45° (45° task)
Group 135° (135° task)
1
2
3
4
Ret.
Day


Variable Error (relative phase)
20
15
10
5
0
Group 45° (0° task)
Group 135° (0° task)
Group 45° (180° task)
Group 135° (180° task)
1
2
3
4
Ret.
Day

Appendix A

Glossary

Attractor Layout - a representation of the energy required to maintain each phase relation. A stable pattern would have a 'basin of attraction'. The lower and narrower the basin, the stronger the attractor. The attractor layout can change through behavioral information.

Attractors - patterns of movement that are stable due to previous influences (e.g. innate tendencies or practice) such that performance of other patterns is biased toward the attractors.

Behavioral Information - information that influences performance of a coordination pattern in the direction specified by the behavioral information. Behavioral information can be memorized, environmental, or intended.

Control Parameter - a variable that creates a non-linear change in the behavior of a system when it changes linearly. Change in the control parameter does not directly specify the direction or type of change in the behavior of the system.

Critical Frequency - usually expressed in Hertz, it is the frequency of oscillation at which a phase transition is observed when the rate of movement is systematically increased. Critical frequency is marked by peak velocity in performance.

Dynamics - description of organization of microscopic elements through macroscopic variables. An attempt to globally describe (through the selection of appropriate variables) the organization of the numerous degrees of freedom that comprise the system.

Intrinsic Patterns - patterns of coordination between two limbs that can be performed spontaneously. In-phase and anti-phase have been shown to be the two intrinsic patterns although Zanone and Kelso (1992b) suggest 90° is an intrinsic pattern for some. Also known as preferred patterns.

Intrinsic Dynamics - the stable coordination tendencies that presently exist including both innate biological constraints and constraints that reflect past experience.

Non-Linear Pattern Change - a change in the performance from one coordination pattern to a new pattern such that the ability to perform all patterns is altered. This may occur through frequency scaling (short term time scale) or through practice on a long term time scale (by formation of a new attractor).

Preferred Patterns - see intrinsic patterns

Relative Phase - the position of each limb is measured in absolute terms. One limb is then made the reference and the other is measured relative to the reference. Relative phase can be measured continuously (sampling rate of 200 Hz) or at the peaks of flexion and extension.

Relaxation Time - the time it takes for the required relative phase to be resurned after a perturbation is applied.

Appendix B

Instructions to Subjects

Instructions to Subjects (90°)

You will be practicing a movement task that requires you to grasp both wooden dowels and move them in a specified pattern. This is a learning study that will examine your performance on the task you practice as well as measuring your performance on two patterns you do not practice. If you have any questions as you read through the instructions, please do not hesitate to ask. Note that the term relative phase refers to the position of the left hand in relation to the right. A full cycle (from 'in' position to 'out' and back 'in') performed by the right hand constitutes 360°. Feel free to briefly practice the described movements as you read through the instructions.

For all Conditions

- move the two wooden dowels such that the attached sliding arms move back and forth between the two pencil marks. The range of movement for each arm should be exactly the distance of the two pencil marks (to the 'in' and 'out' positions).
- the movements should be rhythmic and fluid with the right arm always coinciding with the metronome tone at the 'in' position. There should be no stopping during each trial, the movement is to be continuous.
- each trial lasts for 15 s with the metronome beeping once per second (1 Hz).

In Phase (0° relative phase)

- the right arm should begin at the inner marking ('in' position) coincident with the metronome and the left arm should mirror the movements of the right arm.
- When the right arm reaches the 'in' position so should the left arm and when the right arm arrives at the 'out' position, so should the left.
- start with both arms at the 'in' position.

Anti Phase (180° relative phase)

- the right arm should begin at the 'in' position and the left arm begins at the 'out' position. In this case, the arms should move parallel to each other with the right arm coinciding with the metronome pulse at the 'in' position (like windshield wipers).
- when the right arm is 'out' , the left arm should be 'in' and vice versa.

90° relative phase

- the left arm mirrors the right arm except it follows it by one-quarter of a full cycle.

- again, the right arm must coincide with the metronome beat at the 'in' position.
- when the right arm has reached the 'in' position, the left arm should be at 'middle' position and approaching 'in'. When the right arm is 'out', the left arm should again be at 'middle' position and approaching 'out'.
- start with the right hand at 'in' and the left hand at 'middle'.
- after every 5 trials you will receive feedback on your movement that we will discuss. After each trial you will see an output of your movement that will not be discussed.

Instructions to Subjects (45°)

You will be practicing a movement task that requires you to grasp both wooden dowels and move them in a specified pattern. This is a learning study that will examine your performance on the task you practice as well as measuring your performance on two patterns you do not practice. If you have any questions as you read through the instructions, please do not hesitate to ask. Note that the term relative phase refers to the position of the left hand in relation to the right. A full cycle (from 'in' position to 'out' and back 'in') performed by the right hand constitutes 360°. Feel free to briefly practice the described movements as you read through the instructions.

For all Conditions
- move the two wooden dowels such that the attached sliding arms move back and forth between the two pencil marks. The range of movement for each arm should be exactly the distance of the two pencil marks (to the 'in' and 'out' positions).
- the movements should be rhythmic and fluid with the right arm always coinciding with the metronome tone at the 'in' position. There should be no stopping during each trial, the movement is to be continuous.
- each trial lasts for 15 s with the metronome beeping once per second (1 Hz).

In Phase (0° relative phase)
- the right arm should begin at the inner marking ('in' position) coincident with the metronome and the left arm should mirror the movements of the right arm.
- When the right arm reaches the 'in' position so should the left arm and when the right arm arrives at the 'out' position, so should the left.
- start with both arms at the 'in' position.

Anti Phase (180° relative phase)
- the right arm should begin at the 'in' position and the left arm begins at the 'out' position. In this case, the arms should move parallel to each other with the right arm coinciding with the metronome pulse at the 'in' position (like windshield wipers).
- when the right arm is 'out' , the left arm should be 'in' and vice versa.

45° relative phase
- the left arm mirrors the right arm except it follows it by one-quarter of a half cycle.

- again, the right arm must coincide with the metronome beat at the 'in' position.
- when the right arm has reached the 'in' position, the left arm should be at '45' position and approaching 'in'. When the right arm is 'out', the left arm should be at '135' position and approaching 'out'.
- start with the right hand at 'in' and the left hand at '45'.
- after every 5 trials you will receive feedback on your movement that we will discuss. After each trial you will see an output of your movement that will not be discussed.

Instructions to Subjects (135°)

You will be practicing a movement task that requires you to grasp both wooden dowels and move them in a specified pattern. This is a learning study that will examine your performance on the task you practice as well as measuring your performance on two patterns you do not practice. If you have any questions as you read through the instructions, please do not hesitate to ask. Note that the term relative phase refers to the position of the left hand in relation to the right. A full cycle (from 'in' position to 'out' and back 'in') performed by the right hand constitutes 360°. Feel free to briefly practice the described movements as you read through the instructions.

For all Conditions

- move the two wooden dowels such that the attached sliding arms move back and forth between the two pencil marks. The range of movement for each arm should be exactly the distance of the two pencil marks (to the 'in' and 'out' positions).
- the movements should be rhythmic and fluid with the right arm always coinciding with the metronome tone at the 'in' position. There should be no stopping during each trial, the movement is to be continuous.
- each trial lasts for 15 s with the metronome beeping once per second (1 Hz).

In Phase (0° relative phase)

- the right arm should begin at the inner marking ('in' position) coincident with the metronome and the left arm should mirror the movements of the right arm.
- When the right arm reaches the 'in' position so should the left arm and when the right arm arrives at the 'out' position, so should the left.
- start with both arms at the 'in' position.

Anti Phase (180° relative phase)

- the right arm should begin at the 'in' position and the left arm begins at the 'out' position. In this case, the arms should move parallel to each other with the right arm coinciding with the metronome pulse at the 'in' position (like windshield wipers).
- when the right arm is 'out' , the left arm should be 'in' and vice versa.

135° relative phase

- the left arm mirrors the right arm except it follows it by three-quarters of a half cycle.

- again, the right arm must coincide with the metronome beat at the 'in' position.
- when the right arm has reached the 'in' position, the left arm should be at '135' position and approaching 'in'. When the right arm is 'out', the left arm should be at '45' position and approaching 'out'.
- start with the right hand at 'in' and the left hand at '135'.
- after every 5 trials you will receive feedback on your movement that we will discuss. After each trial you will see an output of your movement that will not be discussed.

Appendix C

ANOVA Tables for Experiment 1

Table C-1

ANOVA Summary Table of Day by Time by Pattern for |CE|.

Source of Variance	df	Sum of Squares	Mean Square	F	p	Omega Squared
Subjects	6	3617.718	602.953			
Day	5	19493.245	3898.649	22.069	.0000	0.130
Error	30	5299.707	176.657			
Time	1	1159.716	1159.716	29.453	.0016	0.008
Error	6	236.247	39.375			
D*T	5	4625.140	925.028	3.708	.0099	0.024
Error	30	7483.743	249.458			
Pattern	2	17323.516	8661.758	21.718	.0001	0.115
Error	12	4785.986	398.832			
D*P	10	39411.534	3941.153	21.890	.0000	0.262
Error	60	10802.778	180.046			
T*P	2	5054.729	2527.365	35.232	.0000	0.034
Error	12	860.828	71.736			
D*T*P	10	9701.586	970.159	4.332	.0001	0.052
Error	60	13436.510	223.942			

Table C-2

ANOVA Summary Table of Day by Time by Pattern for |CE| for Intrinsic Patterns.

Source of Variance	df	Sum of Squares	Mean Square	F	p	Omega Squared
Subjects	6	619.146	103.191			
Day	5	17.260	3.452	0.275	.9230	
Error	30	376.093	12.536			
Time	1	174.461	174.461	6.327	.0456	0.048
Error	6	165.437	27.573			
D*T	5	5.179	1.036	0.118	.9875	
Error	30	264.353	8.812			
Pattern	1	210.829	210.829	4.026	.0916	
Error	6	314.216	52.369			
D*P	5	240.661	48.132	4.796	.0024	0.063
Error	30	301.104	10.037			
T*P	1	8.326	8.326	0.683	.4400	
Error	6	73.094	12.182			
D*T*P	5	39.480	7.896	1.207	.3297	
Error	30	196.200	6.540			

Table C-3

ANOVA Summary Table of Day by Time for |CE| for the 90 Pattern.

Source of Variance	df	Sum of Squares	Mean Square	F	p	Omega Squared
Subjects	6	30958.867	5159.811			
Day	5	140115.185	28023.037	15.213	.0000	0.389
Error	30	55263.118	1842.104			
Time	8	7451.731	931.466	4.237	.0007	0.017
Error	48	10552.769	219.849			
D*T	40	26874.097	671.852	2.531	.0000	0.048
Error	240	63715.332	265.481			

Table C-4

ANOVA Summary Table of Time by Pattern for | CE | for each Day of Pratice.

Day 1

Source of Variance	df	Sum of Squares	Mean Square	F	p	Omega Squared
Subjects	6	6275.196	1045.866			
Time	1	5426.447	5426.447	6.886	.0394	0.045
Error	6	4727.917	787.986			
Pattern	2	51937.719	25968.860	28.300	.0000	0.482
Error	12	11011.701	917.642			
T*P	2	13262.078	6631.039	7.657	.0072	0.111
Error	12	10392.189	866.016			

Day 2

Source of Variance	df	Sum of Squares	Mean Square	F	p	Omega Squared
Subjects	6	1806.182	301.030			
Time	1	253.577	253.577	0.697	.4359	
Error	6	2184.000	364.000			
Pattern	2	4065.258	2032.629	8.187	.0057	0.236
Error	12	2979.269	248.272			
T*P	2	1066.590	533.295	2.561	.1185	
Error	12	2498.923	208.244			

Day 3

Source of Variance	df	Sum of Squares	Mean Square	F	p	Omega Squared
Subjects	6	357.266	59.544			
Time	1	30.515	30.515	0.405	.5481	
Error	6	452.275	75.379			
Pattern	2	248.132	124.066	2.376	.1351	
Error	12	626.658	52.222			
T*P	2	261.878	130.939	1.619	.2368	
Error	12	970.792	80.899			

Day 4

Source of Variance	df	Sum of Squares	Mean Square	F	p	Omega Squared
Subjects	6	118.106	19.684			
Time	1	17.615	17.615	0.635	.4560	
Error	6	166.535	27.756			
Pattern	2	62.560	31.280	1.162	.3457	
Error	12	323.040	26.920			
T*P	2	12.300	6.150	0.743	.4964	
Error	12	99.340	8.278			

Day 5

Source of Variance	df	Sum of Squares	Mean Square	F	p	Omega Squared
Subjects	6	81.555	13.593			
Time	1	0.001	0.001	0.000	.9919	
Error	6	50.449	8.408			
Pattern	2	212.558	106.279	3.334	.0705	
Error	12	382.502	31.875			
T*P	2	148.606	74.303	12.871	.0010	0.144
Error	12	69.274	5.773			

Day 6

Source of Variance	df	Sum of Squares	Mean Square	F	p	Omega Squared
Subjects	6	279.120	46.520			
Time	1	56.701	56.701	2.451	.1685	
Error	6	138.816	23.136			
Pattern	2	208.823	104.412	4.718	.0308	0.132
Error	12	265.593	22.133			
T*P	2	4.863	2.432	0.109	.8973	
Error	12	266.820	22.235			

Table C-5

ANOVA Summary Table of Pattern by Time for |CE| for Retention.

Source of Variance	df	Sum of Squares	Mean Square	F	p	Omega Squared
Subjects	6	306.894	51.149			
Time	2	322.001	161.001	8.548	.0049	0.175
Error	12	226.019	18.835			
Pattern	2	140.247	70.124	3.902	.0495	0.064
Error	12	215.633	17.969			
T*P	4	11.498	2.875	0.178	.9474	
Error	24	386.922	16.122			

Table C-6

ANOVA Summary Table of Day by Time by Pattern for VE.

Source of Variance	df	Sum of Squares	Mean Square	F	p	Omega Squared
Subjects	6	896.514	149.419			
Day	5	3495.485	699.097	25.908	.0000	0.204
Error	30	809.520	26.984			
Time	1	157.938	157.938	5.378	.0595	
Error	6	176.219	29.370			
D*T	5	137.739	27.548	0.947	.4654	
Error	30	872.706	29.090			
Pattern	2	3488.536	1744.268	31.413	.0000	0.205
Error	12	666.331	55.528			
D*P	10	2172.870	217.287	8.219	.0000	0.116
Error	60	1586.318	26.439			
T*P	2	19.798	9.899	0.589	.5701	
Error	12	201.625	16.802			
D*T*P	10	28.692	2.869	0.099	.9998	
Error	60	1742.219	29.037			

Table C-7

ANOVA Summary Table of Day by Time by Pattern for VE for Intrinsic Patterns.

Source of Variance	df	Sum of Squares	Mean Square	F	p	Omega Squared
Subjects	6	217.997	36.333			
Day	5	493.979	98.796	7.104	.0002	0.189
Error	30	417.191	13.906			
Time	1	59.286	59.286	12.270	.0128	0.024
Error	6	28.990	4.832			
D*T	5	97.692	19.538	3.712	.0098	0.032
Error	30	157.902	5.263			
Pattern	1	135.361	135.361	8.484	.0269	0.053
Error	6	95.728	15.955			
D*P	5	44.948	8.990	1.068	.3976	
Error	30	252.533	8.418			
T*P	1	0.115	0.115	0.028	.8718	
Error	6	24.396	4.066			
D*T*P	5	13.511	2.702	0.433	.8220	
Error	30	187.258	6.242			

Table C-8

ANOVA Summary Table of Day by Time for VE for the 90 Pattern.

Source of Variance	df	Sum of Squares	Mean Square	F	p	Omega Squared
Subjects	6	2866.194	477.699			
Day	5	18507.844	3701.569	23.115	.0000	0.524
Error	30	4804.199	160.140			
Time	8	400.735	50.092	2.449	.0261	0.007
Error	48	981.957	20.457			
D*T	40	919.679	22.992	1.066	.3736	
Error	240	5178.093	21.575			

Table C-9

ANOVA Summary Table of Time by Pattern for VE for each Day of Practice.

Day 1

Source of Variance	df	Sum of Squares	Mean Square	F	p	Omega Squared
Subjects	6	987.578	164.596			
Time	1	237.619	237.619	1.582	.2553	
Error	6	901.392	150.232			
Pattern	2	3928.958	1964.479	16.230	.0004	0.400
Error	12	1452.469	121.039			
T*P	2	1.999	1.000	0.008	.9925	
Error	12	1592.955	132.746			

Day 2

Source of Variance	df	Sum of Squares	Mean Square	F	p	Omega Squared
Subjects	6	250.793	41.799			
Time	1	26.720	26.720	3.330	.1178	
Error	6	48.145	8.024			
Pattern	2	1078.195	539.098	28.580	.0000	0.602
Error	12	226.355	18.863			
T*P	2	4.232	2.116	0.338	.7198	
Error	12	75.118	6.260			

Day 3

Source of Variance	df	Sum of Squares	Mean Square	F	p	Omega Squared
Subjects	6	153.141	25.524			
Time	1	18.534	18.534	3.755	.1008	
Error	6	29.615	4.936			
Pattern	2	239.803	119.902	5.773	.0175	0.247
Error	12	249.240	20.770			
T*P	2	26.710	13.355	2.410	.1318	
Error	12	66.487	5.541			

Day 4

Source of Variance	df	Sum of Squares	Mean Square	F	p	Omega Squared
Subjects	6	120.070	20.012			
Time	1	2.726	2.726	0.633	.4565	
Error	6	25.826	4.304			
Pattern	2	197.315	98.658	17.699	.0003	0.387
Error	12	66.892	5.574			
T*P	2	5.138	2.569	0.539	.5967	
Error	12	57.176	4.765			

Day 5

Source of Variance	df	Sum of Squares	Mean Square	F	p	Omega Squared
Subjects	6	108.413	18.069			
Time	1	8.149	8.149	2.135	.1943	
Error	6	22.900	3.817			
Pattern	2	116.731	58.366	4.121	.0434	0.159
Error	12	169.939	14.162			
T*P	2	6.836	3.418	0.373	.6964	
Error	12	109.980	9.165			

Day 6

Source of Variance	df	Sum of Squares	Mean Square	F	p	Omega Squared
Subjects	6	86.040	14.340			
Time	1	1.929	1.929	0.550	.4864	
Error	6	21.048	3.508			
Pattern	2	100.403	50.202	6.865	.0103	0.245
Error	12	87.753	7.313			
T*P	2	3.576	1.788	0.509	.6134	
Error	12	42.128	3.511			

Table C-10

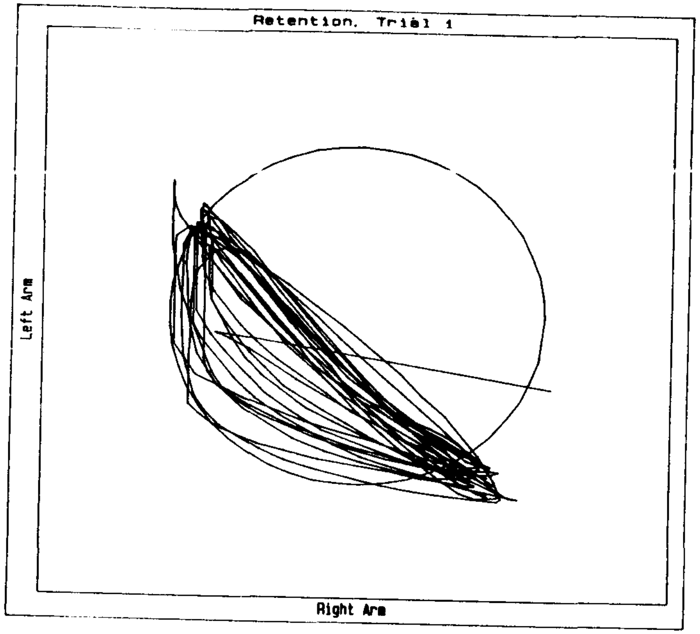
ANOVA Summary Table of Time by Pattern for VE for Retention.

Source of Variance	df	Sum of Squares	Mean Square	F	p	Omega Squared
Subjects	6	108.452	18.075			
Pattern	2	4.290	2.145	0.819	.4642	
Error	12	31.439	2.620			
Time	2	170.310	85.155	10.666	.0022	0.306
Error	12	95.806	7.984			
T*P	4	4.850	1.213	0.362	.8334	
Error	24	80.478	3.353			

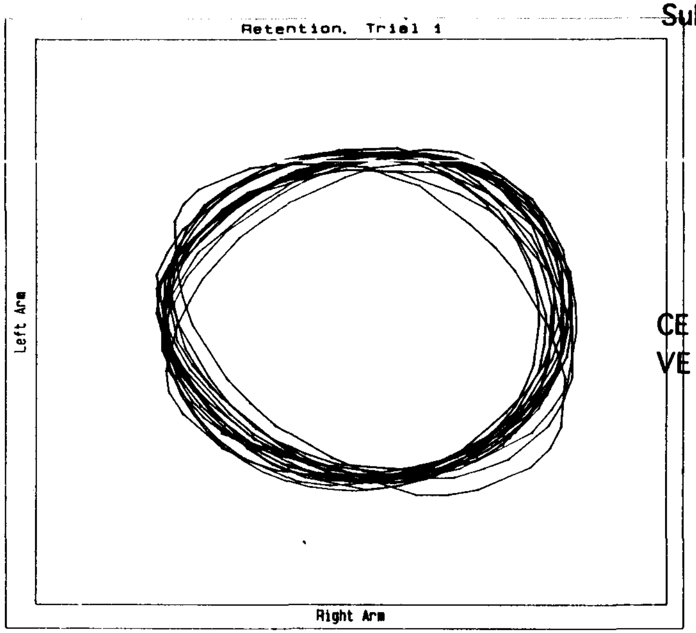
Appendix D

Lissajou Figures

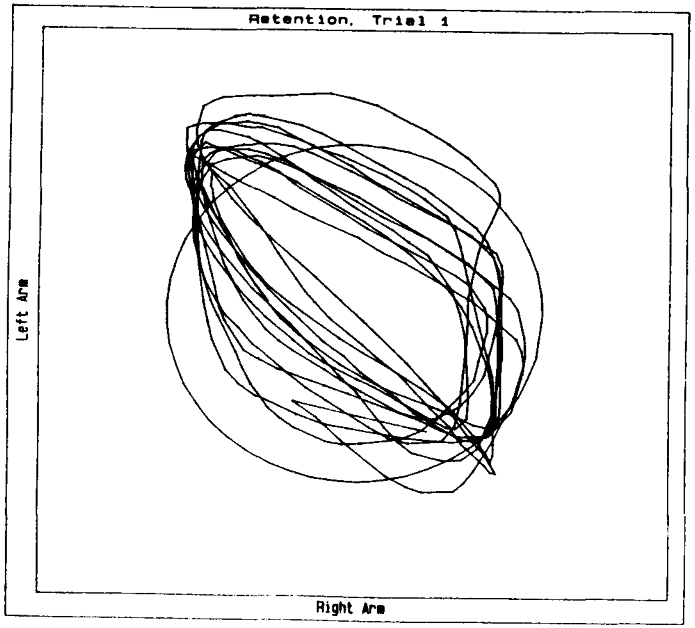
Subject CG



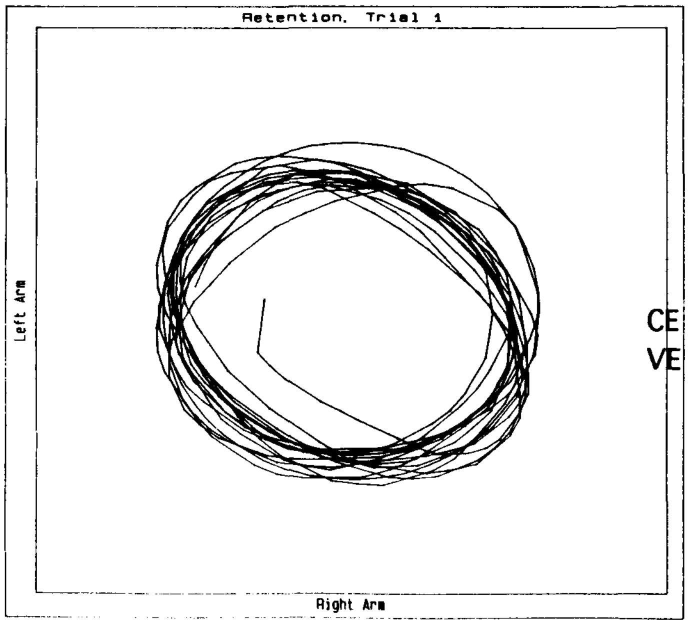
CE = 114.2
VE = 22.1



CE = 7.8
VE = 11.7

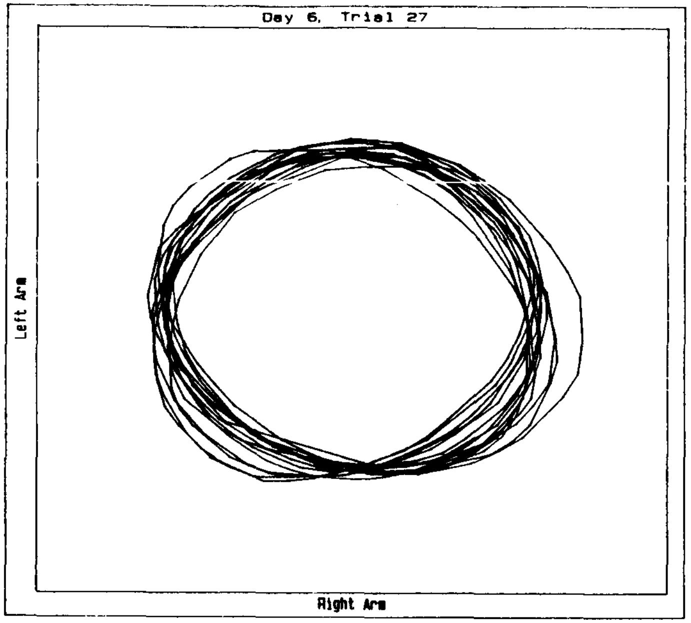


CE = 48.3
VE = 22.0

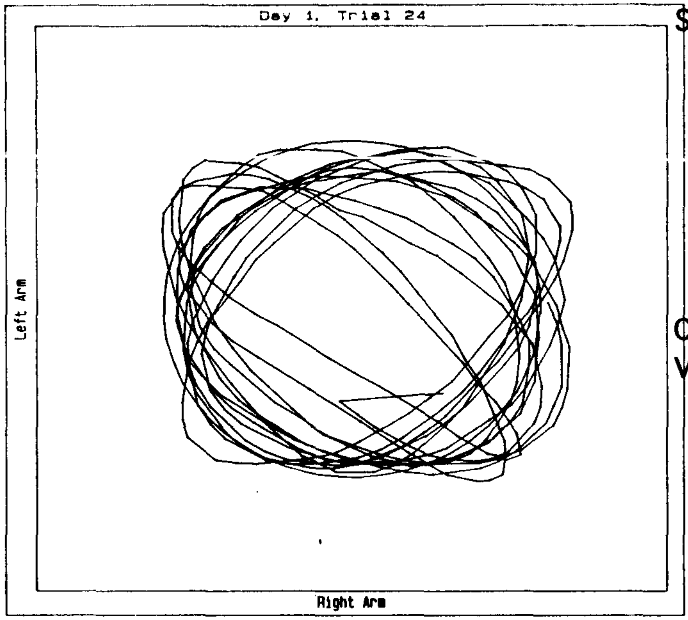


CE = 7.6
VE = 14.4

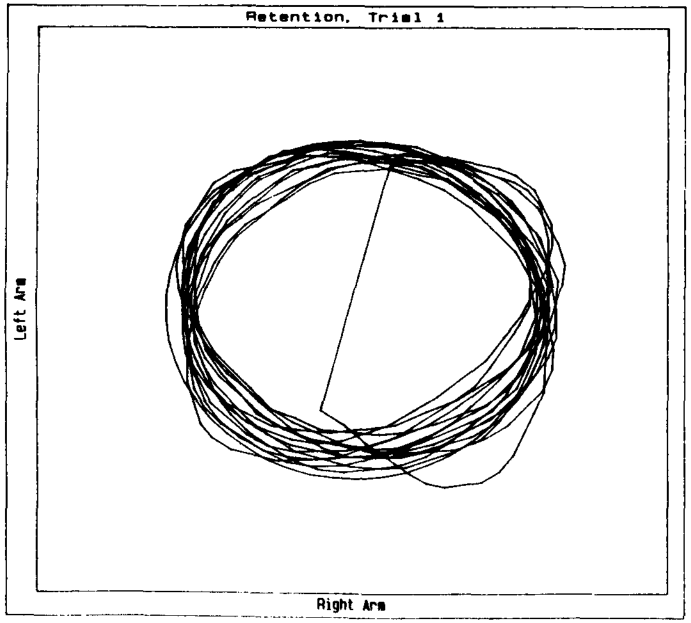
Subject LM



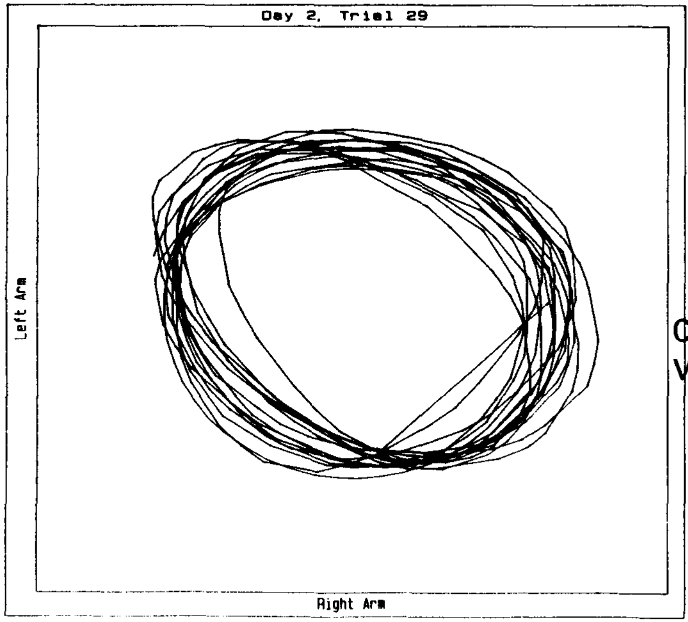
CE = 3.6
VE = 32.8



CE = 0.6
VE = 9.0

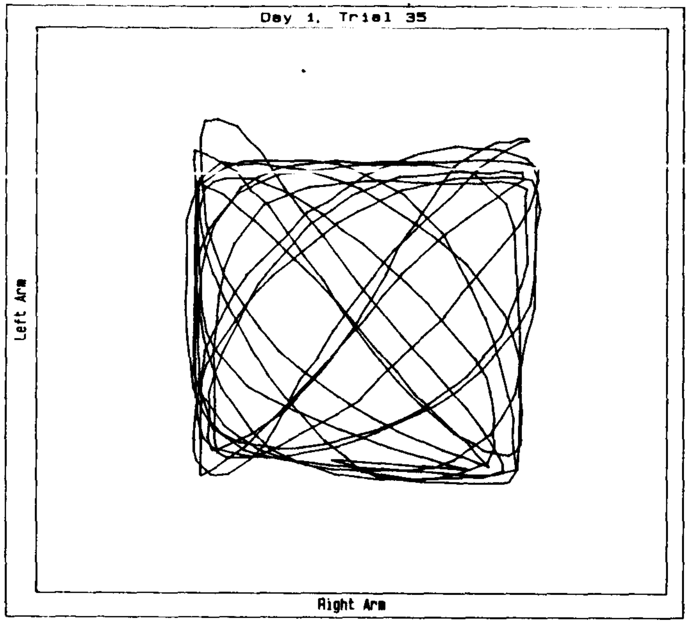


CE = 11.0
VE = 15.2

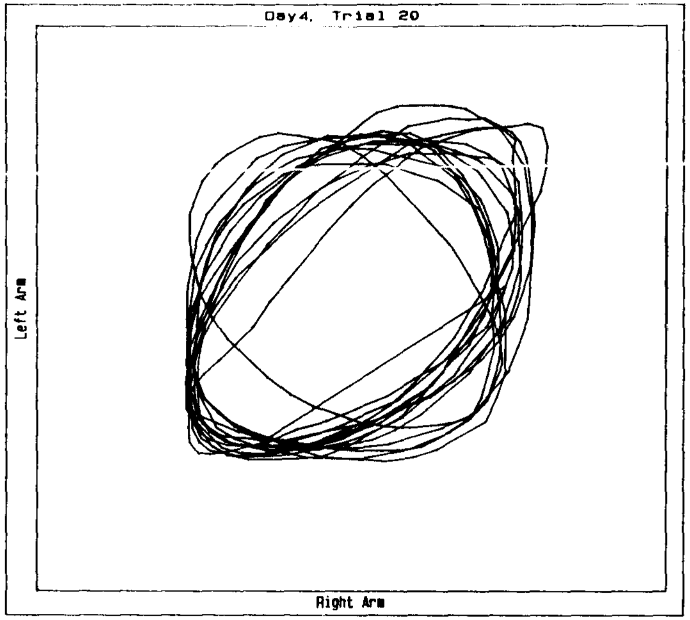


CE = 3.5
VE = 8.2

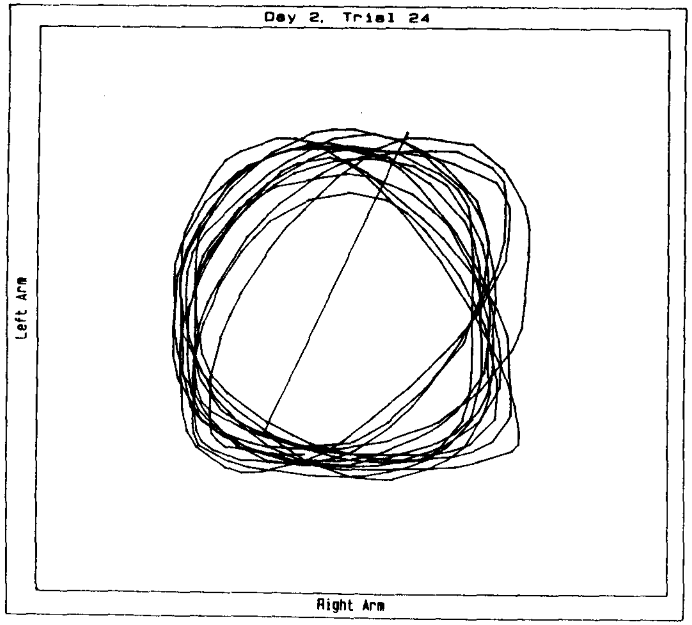
Subject PM



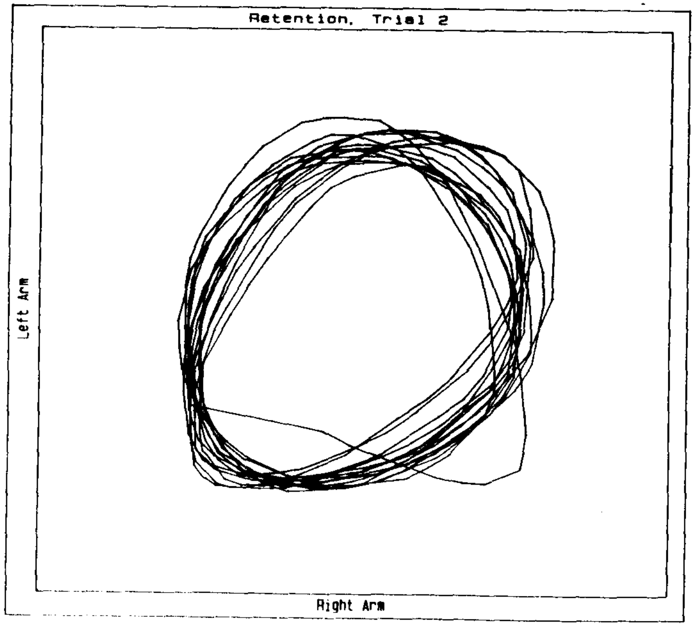
CE = 54.7
VE = 92.3



CE = 26.3
VE = 24.9

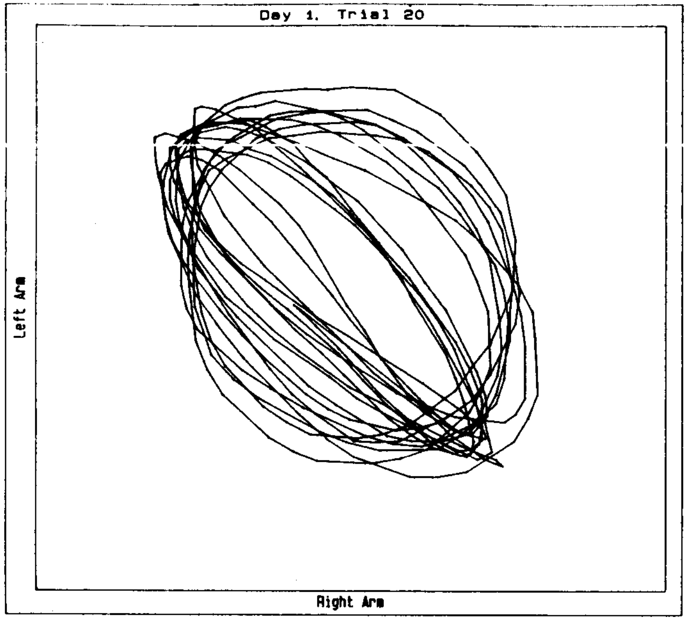


CE = 41.7
VE = 21.5

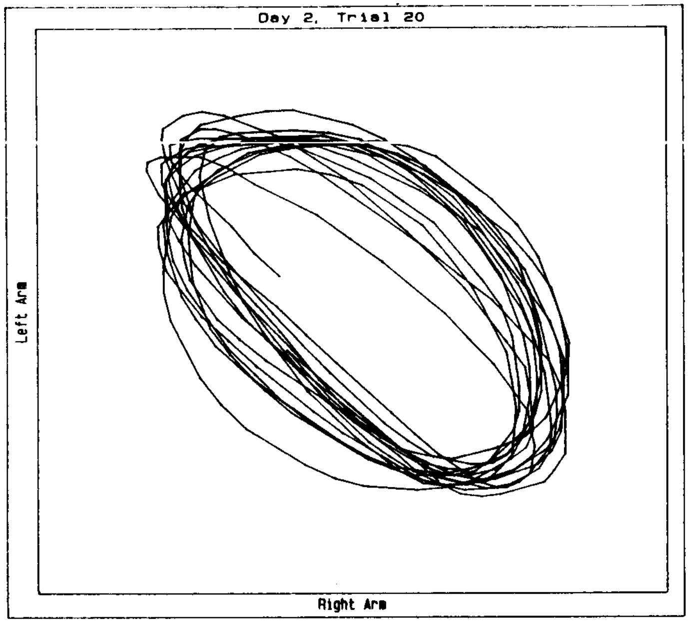


CE = 26.9
VE = 11.5

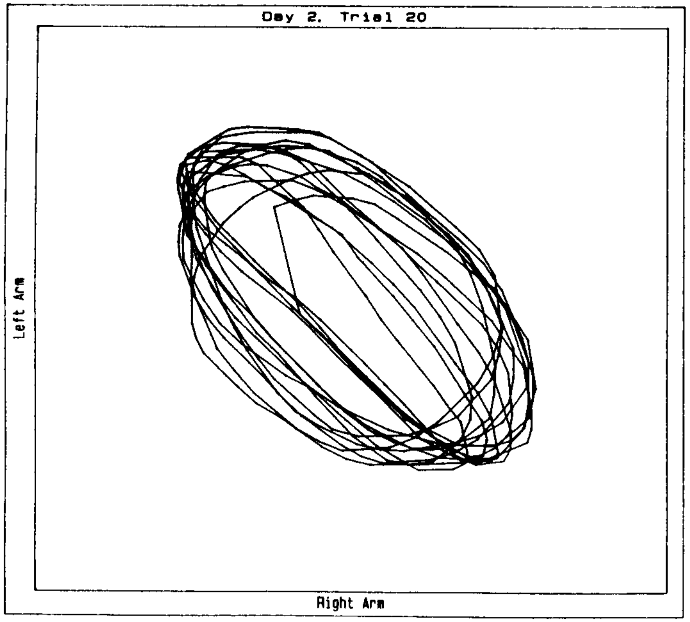
Subject LC



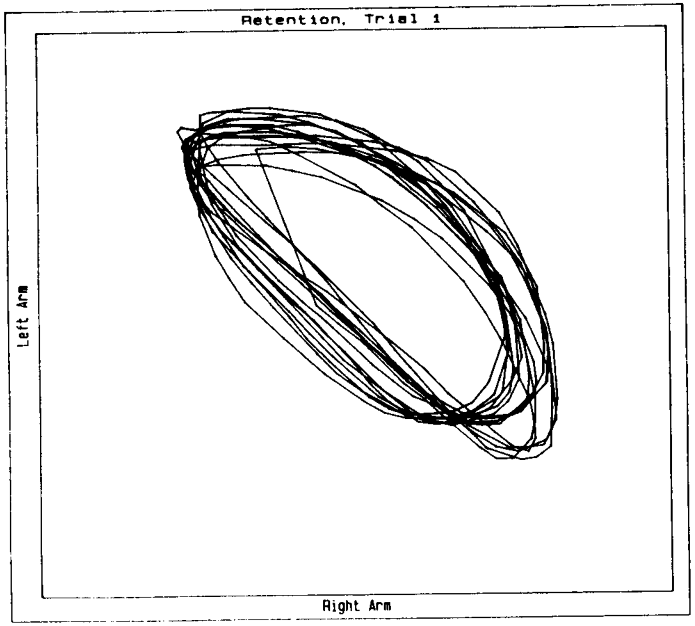
CE = -8.4
VE =22.8



CE = 1.3
VE = 15.8

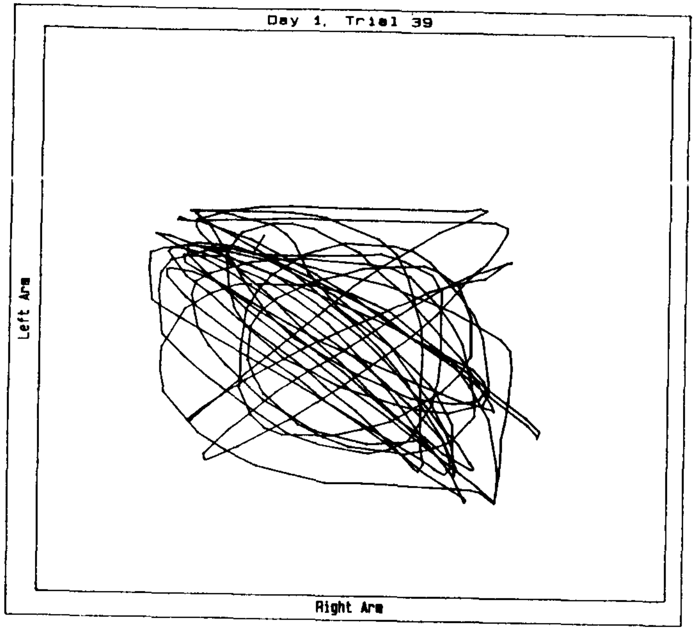


CE = -29.1
VE = 14.2

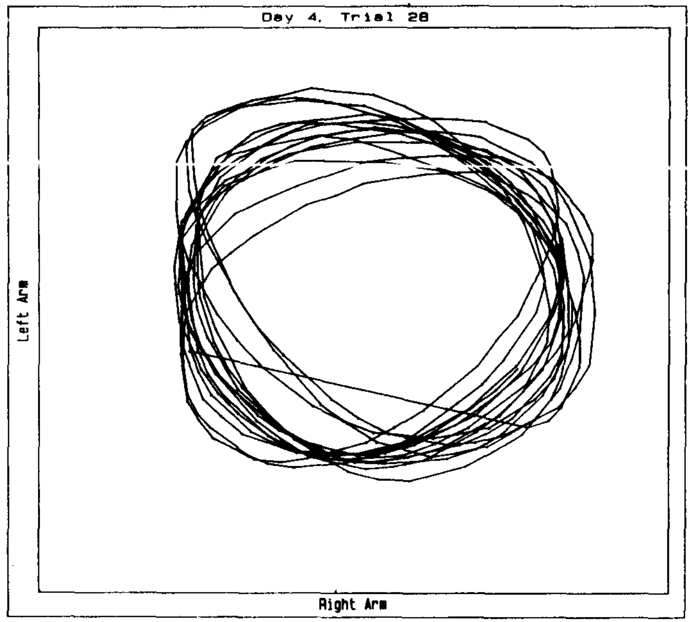


CE = -8.6
VE = 9.4

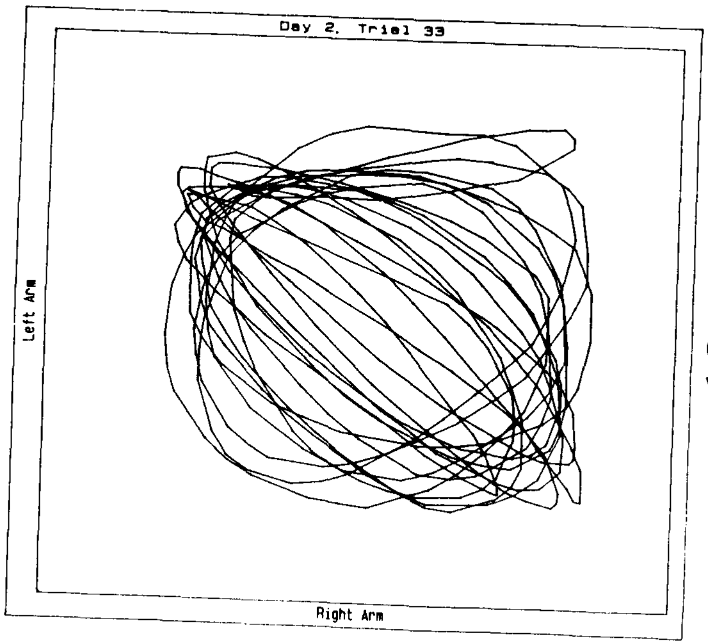
Subject AS



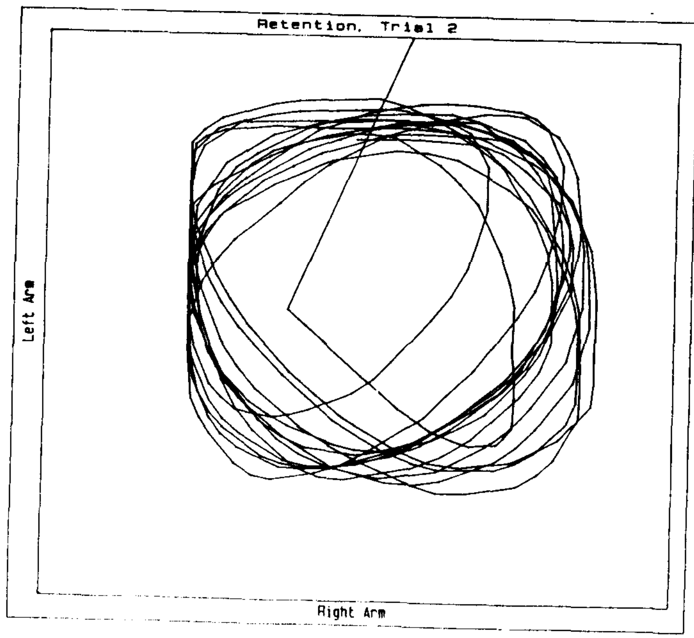
CE = 108.2
VE = 109.5



CE = -39.8
VE = 14.5

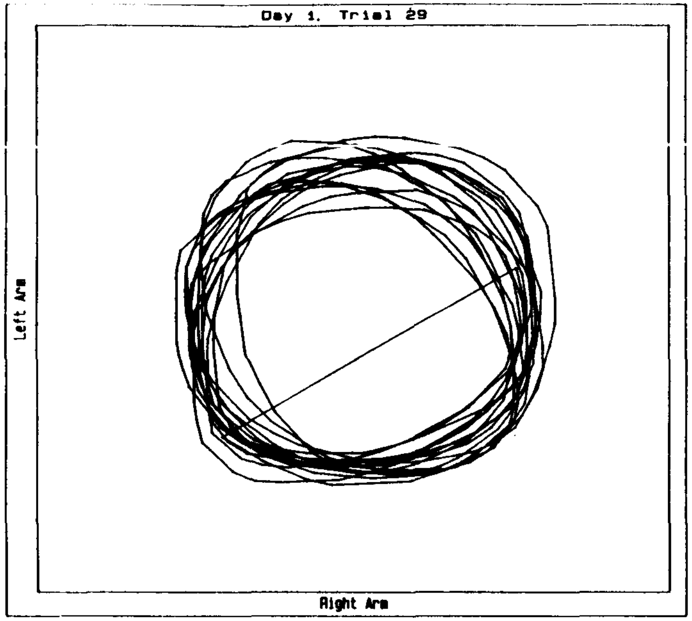


CE = -13.6
VE = 69.8

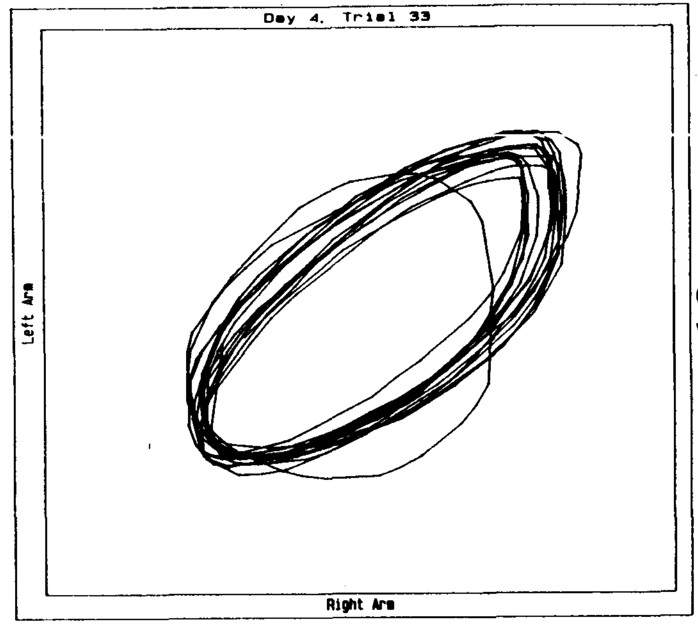


CE = 0.8
VE = 15.3

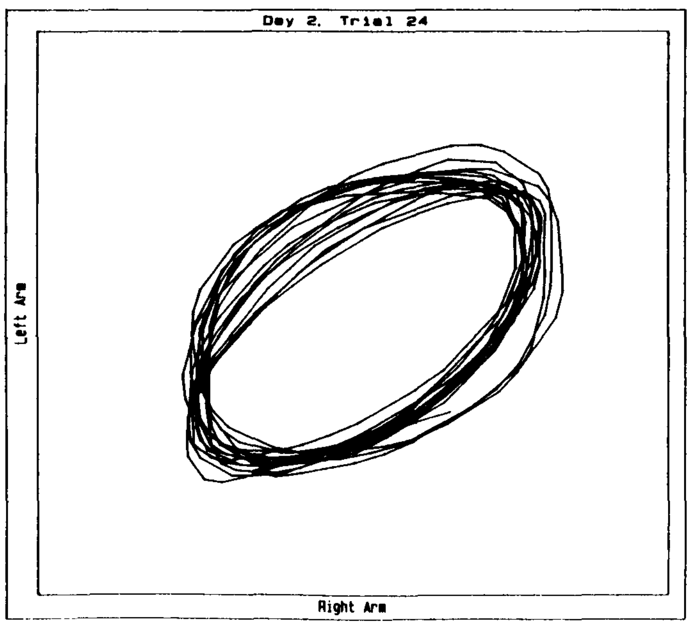
Subject MC



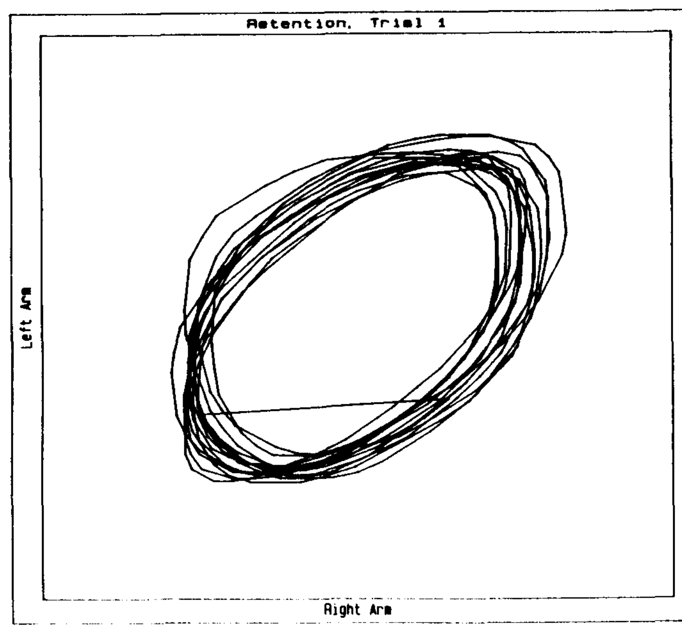
CE = 52.0
VE = 12.7



CE = -3.4
VE = 11.0



CE = 15.5
VE = 10.2



CE = 0.5
VE = 9.8

Appendix E

ANOVA Tables for Experiment 2

Table E-1

ANOVA Summary Table of Group by Day by Time by Pattern for |CE|.

Source of Variance	df	Sum of Squares	Mean Square	F	p	Omega Squared
Group	1	15.401	15.401	0.013	.9109	
Error	10	11701.359	1170.136			
Day	3	5408.688	1802.896	10.253	.0001	0.036
G*D	3	235.865	78.622	0.447	.7211	
Error	30	5275.327	175.844			
Time	1	1099.805	1099.805	7.702	.0196	0.007
G*T	1	44.494	44.494	0.312	.5890	
Error	10	1427.864	142.786			
D*T	3	806.950	268.983	2.024	.1316	
G*D*T	3	303.498	101.166	0.761	.5246	
Error	30	3986.139	132.871			
Pattern	2	43574.815	21787.408	22.220	.0000	0.303
G*P	2	383.776	191.888	0.196	.8238	
Error	20	19610.536	980.527			
D*P	6	10270.046	1711.674	8.490	.0000	0.066
G*D*P	6	1532.880	255.480	1.267	.2861	
Error	60	12097.210	201.620			
T*P	2	4314.248	2157.124	17.608	.0000	0.030
G*T*P	2	701.500	350.750	2.863	.0806	
Error	20	2450.099	122.505			
D*T*P	6	1311.068	218.511	1.421	.2215	
G*D*T*P	6	357.892	59.649	0.388	.8839	
Error	60	9225.603	153.760			

Table E-2

ANOVA Summary Table of Group by Day by Time by Pattern for |CE| for Intrinsic Patterns.

Source of Variance	df	Sum of Squares	Mean Square	F	p	Omega Squared
Group	1	349.845	349.845	2.743	.1287	
Error	10	1275.585	127.559			
Day	3	140.422	46.807	2.657	.0663	
G*D	3	179.263	59.754	3.393	.0306	0.021
Error	30	528.408	17.614			
Time	3	194.481	64.827	12.899	.0000	0.030
G*T	3	98.263	32.754	6.517	.0016	0.014
Error	30	150.771	5.026			
D*T	9	69.830	7.759	1.076	.3882	
G*D*T	9	74.063	8.229	1.141	.3426	
Error	90	648.909	7.210			
Pattern	1	270.472	270.472	4.907	.0511	
G*P	1	234.961	234.961	4.263	.0659	
Error	10	551.175	55.118			
D*P	3	62.604	20.868	1.463	.2445	
G*D*P	3	21.048	7.016	0.492	.6906	
Error	30	427.992	14.266			
T*P	3	6.048	2.016	0.452	.7177	
G*T*P	3	3.941	1.314	0.295	.8290	
Error	30	133.785	4.460			
D*T*P	9	45.887	5.099	0.782	.6334	
G*D*T*P	9	19.323	2.147	0.329	.9632	
Error	90	586.790	6.520			

Table E-3

ANOVA Summary Table of Group by Day by Time by Pattern for |CE| of the Practiced Patterns (45 and 135).

Source of Variance	df	Sum of Squares	Mean Square	F	p	Omega Squared
Group	1	1733.204	1733.204	0.155	.7023	
Error	10	112028.898	11202.890			
Day	3	54438.167	18146.056	19.169	.0000	0.182
G*D	3	3605.941	1201.980	1.270	.3025	
Error	30	28398.906	946.630			
Time	8	6000.315	750.039	3.769	.0009	0.016
G*T	8	2274.753	284.344	1.429	.1973	
Error	80	15918.495	198.981			
D*T	24	5898.562	245.773	1.227	.2191	
G*D*T	24	4790.530	199.605	0.997	.4715	
Error	240	48071.522	200.298			

Table E-4

ANOVA Summary Tables of Group by Time by Pattern for |CE| for each Day of Practice.

Day 1

Source of Variance	df	Sum of Squares	Mean Square	F	p	Omega Squared
Group	1	53.734	53.734	0.101	.7571	
Error	10	5318.397	531.840			
Time	1	1235.045	1235.045	3.323	.0983	
G*T	1	12.500	12.500	0.034	.8582	
Error	10	3716.768	371.677			
Pattern	2	32733.094	16366.547	31.808	.0000	0.495
G*P	2	329.129	164.565	0.320	.7299	
Error	20	10290.928	514.546			
T*P	2	3218.411	1609.206	4.880	.0188	0.040
G*T*P	2	81.866	40.933	0.124	.8839	
Error	20	6595.660	329.783			

Day 2

Source of Variance	df	Sum of Squares	Mean Square	F	p	Omega Squared
Group	1	78.333	78.333	0.109	.7477	
Error	10	7163.828	716.383			
Time	1	655.823	655.823	4.900	.0511	
G*T	1	313.751	313.751	2.344	.1567	
Error	10	1338.354	133.835			
Pattern	2	14024.941	7012.471	11.108	.0006	0.294
G*P	2	73.381	36.691	0.058	.9437	
Error	20	12625.424	631.271			
T*P	2	1856.658	928.329	4.883	.0188	0.034
G*T*P	2	813.370	406.685	2.139	.1439	
Error	20	3802.059	190.103			

Day 3

Source of Variance	df	Sum of Squares	Mean Square	F	p	Omega Squared
Group	1	5.445	5.445	0.023	.8823	
Error	10	2359.069	235.907			
Time	1	10.276	10.276	0.895	.3664	
G*T	1	80.134	80.134	6.981	.4196	
Error	10	114.781	11.478			
Pattern	2	3723.419	1861.710	8.999	.0016	0.272
G*P	2	447.006	223.503	1.080	.3585	
Error	20	4137.506	206.875			
T*P	2	399.924	199.962	7.290	.0042	0.029
G*T*P	2	153.375	76.688	2.796	.0850	
Error	20	548.571	27.429			

Day 4

Source of Variance	df	Sum of Squares	Mean Square	F	p	Omega Squared
Group	1	113.753	113.753	0.533	.4822	
Error	10	2135.391	213.539			
Time	1	5.611	5.611	0.230	.6419	
G*T	1	13.607	13.607	0.557	.4725	
Error	10	244.100	24.410			
Pattern	2	3363.408	1681.704	7.227	.0043	0.228
G*P	2	1067.141	533.571	2.293	.1269	
Error	20	4653.888	232.694			
T*P	2	150.323	75.162	2.061	.1535	
G*T*P	2	10.781	5.391	0.148	.8635	
Error	20	729.412	36.471			

Table E-5

ANOVA Summary Tables of Pattern by Time for |CE| on Retention for both Practice Groups.

45 Group

Source of Variance	df	Sum of Squares	Mean Square	F	p	Omega Squared
Subjects	5	1211.792	242.358			
Pattern	2	821.491	410.746	1.464	.2768	
Error	10	2804.962	280.496			
Time	2	26.962	13.481	0.663	.5420	
Error	10	203.237	20.324			
P*T	4	160.830	40.208	1.015	.4233	
Error	20	792.137	39.607			

135 Group

Source of Variance	df	Sum of Squares	Mean Square	F	p	Omega Squared
Subjects	5	2688.612	537.722			
Pattern	2	5828.007	2914.004	7.161	.0117	0.365
Error	10	4069.284	406.928			
Time	2	34.758	17.379	0.634	.5503	
Error	10	273.940	27.394			
P*T	4	51.706	12.927	0.669	.6212	
Error	20	386.556	19.328			

Table E-6

ANOVA Summary Table of Group by Day by Time by Pattern for VE.

Source of Variance	df	Sum of Squares	Mean Square	F	p	Omega Squared
Group	1	71.302	71.302	0.256	.6240	
Error	10	2787.358	278.736			
Day	3	2906.382	968.794	14.673	.0000	0.063
G*D	3	94.902	31.634	0.479	.6992	
Error	30	1980.722	66.024			
Time	1	79.485	79.485	0.710	.4191	
G*T	1	336.918	336.918	3.009	.1134	
Error	10	1119.529	111.953			
D*T	3	34.337	11.446	0.158	.9239	
G*D*T	3	879.122	293.041	4.037	.0159	0.019
Error	30	2177.638	72.588			
Pattern	2	8688.273	4344.137	18.647	.0000	0.191
G*P	2	260.717	130.359	0.560	.5802	
Error	20	4659.462	232.973			
D*P	6	3503.669	583.945	7.691	.0000	0.071
G*D*P	6	210.949	35.158	0.463	.8329	
Error	60	4555.610	75.927			
T*P	2	2.353	1.177	0.014	.9858	
G*T*P	2	586.069	293.035	3.567	.0473	0.010
Error	20	1643.073	82.154			
D*T*P	6	43.358	7.226	0.091	.9970	
G*D*T*P	6	1374.336	229.056	2.898	.0151	0.021
Error	60	4741.878	79.031			

Table E-7

ANOVA Summary Table of Group by Day by Time by Pattern for VE for Intrinsic Patterns.

Source of Variance	df	Sum of Squares	Mean Square	F	p	Omega Squared
Group	1	1.300	1.300	0.037	.8518	
Error	10	353.935	35.394			
Day	3	46.682	15.561	1.113	.3595	
G*D	3	35.202	11.734	0.839	.4832	
Error	30	419.580	13.986			
Time	1	2.613	2.613	0.192	.6709	
G*T	1	5.535	5.535	0.406	.5385	
Error	10	136.438	13.644			
D*T	3	44.373	14.791	1.405	.2606	
G*D*T	3	33.500	11.167	1.061	.3804	
Error	30	315.821	10.527			
Pattern	1	0.368	0.368	0.051	.8266	
G*P	1	9.452	9.452	1.301	.2806	
Error	10	72.637	7.264			
D*P	3	24.925	8.308	0.844	.4806	
G*D*P	3	22.556	7.519	0.764	.5232	
Error	30	295.263	9.842			
T*P	1	1.613	1.613	0.136	.7201	
G*T*P	1	19.635	19.635	1.654	.2274	
Error	10	118.713	11.871			
D*T*P	3	68.984	22.995	2.880	.0523	
G*D*T*P	3	14.344	4.781	0.599	.6207	
Error	30	239.531	7.984			

Table E-8

ANOVA Summary Table of Group by Day by Time by Pattern for VE of the Practiced Patterns (45 and 135).

Source of Variance	df	Sum of Squares	Mean Square	F	p	Omega Squared
Group	1	3317.242	3317.242	1.778	.2120	
Error	10	18656.524	1865.652			
Day	3	23462.362	7820.787	12.810	.0000	0.217
G*D	3	4524.268	1508.089	2.470	.0810	
Error	30	18316.330	610.544			
Time	8	554.729	69.341	0.981	.4571	
G*T	8	334.960	41.870	0.592	.7815	
Error	80	5655.063	70.688			
D*T	24	1349.735	56.239	0.625	.9148	
G*D*T	24	1334.639	55.610	0.618	.9198	
Error	240	21610.198	90.042			

Table E-9

ANOVA Summary Tables of Group by Time by Pattern for VE for each Day of Practice.

Day 1

Source of Variance	df	Sum of Squares	Mean Square	F	p	Omega Squared
Group	1	9.102	9.102	0.055	.8200	
Error	10	1668.136	166.814			
Time	1	59.769	59.769	0.205	.6605	
G*T	1	1207.042	1207.042	4.138	.0693	
Error	10	2917.062	291.706			
Pattern	2	8545.110	4272.555	20.107	.0000	0.305
G*P	2	97.969	48.985	0.231	.7962	
Error	20	4249.744	212.487			
T*P	2	18.970	9.485	0.033	.9673	
G*T*P	2	1911.469	955.735	3.357	.0553	
Error	20	5694.618	284.731			

Day 2

Source of Variance	df	Sum of Squares	Mean Square	F	p	Omega Squared
Group	1	156.056	156.056	0.600	.4565	
Error	10	2601.352	260.135			
Time	1	31.205	31.205	1.282	.2840	
G*T	1	0.161	0.161	0.007	.9369	
Error	10	243.451	24.345			
Pattern	2	2787.090	1393.545	6.299	.0076	0.207
G*P	2	349.839	174.920	0.791	.4672	
Error	20	4424.408	221.220			
T*P	2	5.643	2.822	0.116	.8911	
G*T*P	2	4.725	2.363	0.097	.9078	
Error	20	486.356	24.318			

Day 3

Source of Variance	df	Sum of Squares	Mean Square	F	p	Omega Squared
Group	1	0.823	0.823	0.024	.8800	
Error	10	343.548	34.355			
Time	1	22.781	22.781	2.828	.1236	
G*T	1	1.361	1.361	0.169	.6897	
Error	10	80.563	8.056			
Pattern	2	516.968	258.484	14.490	.0001	0.308
G*P	2	21.404	10.702	0.600	.5584	
Error	20	356.764	17.838			
T*P	2	15.123	7.562	0.873	.4329	
G*T*P	2	10.830	5.415	0.625	.5452	
Error	20	173.157	8.658			

Day 4

Source of Variance	df	Sum of Squares	Mean Square	F	p	Omega Squared
Group	1	0.222	0.222	0.014	.9071	
Error	10	155.044	15.504			
Time	1	0.067	0.067	0.012	.9150	
G*T	1	7.476	7.476	1.333	.2752	
Error	10	56.091	5.609			
Pattern	2	342.774	171.387	18.613	.0000	0.392
G*P	2	2.454	1.227	0.133	.8760	
Error	20	184.154	9.208			
T*P	2	5.974	2.987	1.938	.1700	
G*T*P	2	33.381	16.691	10.831	.0007	0.037
Error	20	30.821	1.541			

Table E-10

ANOVA Summary Tables of Pattern by Time for VE on Retention for both Practice Groups.

45 Group

Source of Variance	df	Sum of Squares	Mean Square	F	p	Omega Squared
Subjects	5	85.184	17.037			
Pattern	2	188.101	94.051	10.069	.0040	0.336
Error	10	93.410	9.341			
Time	2	12.250	6.125	1.775	.2189	
Error	10	34.501	3.450			
P*T	4	28.162	7.041	2.660	.0628	
Error	20	52.940	2.647			

135 Group

Source of Variance	df	Sum of Squares	Mean Square	F	p	Omega Squared
Subjects	5	102.763	20.553			
Pattern	2	175.700	87.850	14.198	.0012	0.319
Error	10	61.877	6.188			
Time	2	4.896	2.448	0.425	.6648	
Error	10	57.549	5.755			
P*T	4	41.150	10.288	3.369	.0291	0.057
Error	20	61.079	3.054			