INVARIANT RELATIVE TIMING

IN THE LEARNING OF A PERCEPTUAL MOTOR SKILL

by

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ABSTRACT

The concept of invariant relative timing has typically been associated with the concept of a generalized motor program. The present study approaches the phenomenon of invariant relative timing from the perspective of learning. The underlying question of concern for this study is *"What is learned?"*. The specific question addressed by the present study is whether relative timing is one of the essential properties of movement that is learned during skill acquisition. In the present experiment, subjects were given extensive practice in learning to visually track and reproduce a criterion waveform using a joystick control for their response. In order to test whether subjects learn the relative timing of a movement, they were transferred to waveforms which were identical to the criterion in terms of relative timing, but different in terms of absolute timing. Measurements were taken on all waveforms in two conditions: 1) in a pursuit tracking condition where subjects were temporally constrained by the stimulus, and 2) in a reproduction condition where subjects' timing was not constrained. Pursuit tracking performance was evaluated using three dependent measures: RMS error, lead-lag index, and variability. Performance in the reproduction condition was subjected to three analyses: 1) an harmonic analysis, which described each response waveform in terms of its phase, frequency, amplitude, and period; 2) proportional

interval durations; and 3) proportional interval displacements. The outcome from both conditions gives support to the idea that the invariant relative timing of a movement is one of the aspects of a movement that humans learn.

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CHAPTER 1.

INTRODUCTION

One of the fundamental questions for those of us who seek to understand learning is *"what is learned?"*. This question has been central to psychology at least as far back as the inception of behaviorism in the 1930's (Gibson, 1969; Weimer, 1977; Whiting, 1980). The behaviorists have proposed, that it is associations between stimuli and responses that are learned. The cognitivists, on the other hand, have argued, that *what is learned* are representations of movement, objects, or events. There has been much speculation as to the nature of this representation for learned movements; it has been described in different ways by different researchers, with labels such as schema (Schmidt, 1975) image of achievement (Pribram, 1971), and motor program (Keele, 1975).

The Gibsonians or the ecological group, who like the behaviorists, have rejected explanations based on representation, have explained learning in yet another way. J.J. Gibson (1966, p.279) has defined perceptual learning as "cases of perceiving or detecting an invariant". J.J. Gibson's idea can be extended to both the cognitive and motor domains. In relation to cognition, Eleanor Gibson (1969, p471) has argued that the learned perceptual ability "to detect regularity, order, and structure" provides the basis for cognitive abilities such as learning mathematics

(see also Wertheimer, 1945). In the case of movement as well, there are certain of its features that become invariant as it becomes well learned.

The studies that constitute this thesis were conducted in order to investigate the question *"what is learned?"* in the process of perceptual-motor learning. In the field of motor learning and control there have been several hypotheses put forward in an attempt to answer this question. Two of these were the focus of this study. The first of these was that people learn the relative timing of a movement. The second of these, addressed in the pilot study (appendix), was that people learn the component frequencies of a movement.

For several years there has been evidence that the relative timing of the response elements that make up a movement remain invariant over changes in absolute timing during the performance of motor skills. Motor theorists have inferred, from this evidence, that relative timing may be an invariant feature of the central representation (usually motor program) of the movement being learned (Shapiro & Schmidt, 1982; Shapiro, Zernicke, Gregor, & Diestel, 1981). From another perspective, action theorists, though having rejected the notion of representation, nevertheless have argued that invariant relative timing is one of the essential variables that characterizes human skilled action (Kelso, Putnam, & Goodman, 1983; Tuller & Kelso, 1984).

Most of the researchers who have studied invariant relative timing have studied it in relation to the motor program. A central question for those who study the motor program has been "What are its invariant features?", and it has been suggested (Schmidt, 1988) that relative timing is one of these invariant features. The idea that relative timing is an invariant feature of the motor program is often referred to in the literature as the *proportional duration model* (Gentner, 1987). The proportional duration model predicts that any skilled movement performed with different overall durations will exhibit fixed relative durations. Original evidence for this came from some unpublished studies by Armstrong (1970, cited in Schmidt, 1988). He had his subjects repeatedly move a lever through a particular unidimensional spatial-temporal pattern. When subjects moved too quickly they nonetheless maintained an invariance in the relative timing between reversals. It was proposed that this occurred because relative timing was structured into the motor program, whereas the overall duration was a parameter whose value could vary across instances of the skill. Thus, for each instance of the skill a different parameter value for overall duration was assigned to the motor program. This proportional duration model of timing in skilled motor performance has been widely accepted up until now. (For other empirical research supporting this model see: Carter & Shapiro, 1984; Shapiro, 1977; Summers, 1977; Terzuolo & Viviani, 1979).

Recently, however, the concept of invariant relative timing has come into question Gentner (1987). Gentner reanalyzed some of the data from past studies on invariant relative timing. He argued that the majority of the data used as supporting evidence for the proportional duration model had been analyzed imprecisely in that researchers had analyzed mean durations of a given interval instead of individual observed durations. To overcome this problem, Gentner proposed a constant proportion test (see Review of Literature). After having reanalyzed the data from experiments that had found evidence for invariant relative timing in motor tasks, Gentner concluded that the proportional duration model was not supported. Relative durations were maintained to some extent but not precisely. Since the publication of Gentner's paper several researchers have begun to question the phenomenon of invariant relative timing (Heuer, 1988a; Heuer, 1988b; Heuer & Schmidt, 1988; Schmidt, 1988; Zelaznik et al., 1986).

Though humans may not *exhibit* relative timing with perfect invariance, one cannot rule out the notion that they may *learn* invariant relative timing. One could posit at least three reasons for a lack of perfect invariance evident at the behavioral level. The first has been suggested by Heuer (1988), who has argued that a lack of invariance in relative timing at the behavioral level does not necessarily indicate a lack of invariance centrally. This is because there are non-linearities in the nervous system which may

distort a central invariance in relative timing, such that it would manifest peripherally (behaviorally) in the form of variable relative timing.

The second is that humans may learn relative timing in a formal way (Thompson, 1952). As Bateson (1982) has pointed out in describing morphogenesis, though there may be an "asymmetry in size", one nevertheless finds "a deeper symmetry in formal relations". In the same way that symmetry of form organizes morphogenesis, relative timing may be the structure around which a movement pattern is organized. Several authors have drawn parallels between morphogenesis and motor learning (Berkinblit, Feldman, & Fukson, 1986 p.599; Turvey, 1986 p.624). Living creatures exhibit symmetry in terms of form, but rarely is this expressed in terms of perfectly equivalent magnitudes on the right and left sides of the body. For instance, the right leg may be slightly longer than the left (i.e. the magnitudes are not exactly equivalent) but the form is symmetrical in that there are two legs, two knees, two feet and the form of these on the right is the exact mirror image of that on the left. The concept of relative timing can be considered in a similar light. Gentner (1987) has given evidence that interval durations are not always mathematically perfect proportions of overall movement time. This is analogous to Bateson's notion of "asymmetry in size". Gentner also has given evidence that on average the proportions are invariant, and this can be thought of as

analogous to Bateson's notion of the "deeper symmetry in formal relations".

The third reason that relative timing may not exhibit perfect invariance, is that feedback may somehow be involved in modulating the expression of relative timing. Intervals that are not perfect proportions of overall movement time, create problems for the present model of a motor program with fixed relative timing and an overall duration parameter. In such a model relative timing must be maintained precisely. The duration parameter once put into the program is not modifiable. If, however, feedback were being used throughout the duration of the movement to control absolute timing, this might account for slight variations in relative timing. There has been evidence for this in tracking studies (Franks & Wilberg, 1982). In this study, when visual feedback from the stimulus was available, subjects maintained the absolute duration, whereas when this feedback was not available the absolute duration varied.

Another reason, that invariant relative timing is not found in movement production tasks, is that few researchers have considered the necessity of practice in the development of relative timing. For instance, in the recent study by Heuer and Schmidt (1988), in which subjects were given only 250 cycles of practice, it was concluded that relative timing does not remain invariant in a transfer task. However it is questionable whether 250 cycles is adequate practice for the development of invariant relative timing,

or for the development of a motor program. The development
of the motor program is presumably based on extensive
experience with the environment such that an appropriate
form of organization might develop. But, since neither
learning, nor the development of the motor program, are
addressed, the problem of adequate practice is often over-
looked. With insufficient practice, it is not surprising
that the invariance that is deemed to exist within the
program has not been found. Subjects have not been given
sufficient time to develop that invariance. Thus, despite
recent criticsm by Gentner (1987) of the invariant relative
timing hypothesis, the evidence presented above indicates
that invariant relative timing remains a viable topic of
investigation.

The assumption underlying most of the research on
invariant relative timing has been that, invariant relative
timing manifests on a behavioral level because it is
structured into the motor program. Thus relative timing is
invariant, and is seen to function in an open loop fashion,
while overall duration is a parameter left free to vary.
But in motor programming theory, the way in which the
overall duration parameter value is determined and assigned
has not been addressed. The computer analogy may be
misleading in this case, in that in a computer program the
task of assigning and determining parameter values is taken
care of by the programmer. If one assumes that a similar
process is occurring in humans, one is led to the dubious

conclusion that there is a computer programmer (or homunculus) in ones head whose job it is to determine and assign parameter values. The crucial question of the way in which feedback interacts with the program in timing control is relegated to the realm of the programmer/homunculus. Because a computer does not have that dynamic interaction with its environment, that is characteristic of living systems, the computer metaphor can be both limiting and misleading (Carello et al., 1984). In investigating relative timing, I am not assuming the existence of a motor program, nor that relative timing functions within the context of a motor program.

The present study was designed to investigate the development of invariant relative timing in skilled movement. It was carried out partly as a result of the recent controversy, as to whether invariant relative timing is a characteristic of skilled movement (Gentner, 1987; Heuer, 1988; Heuer & Schmidt, 1988). As has been put forward above, the present view of invariant relative timing in human skilled action is different than that proposed by most motor programming theorists (e.g. Schmidt, 1988).

Because I see skilled human action to be characterized by a *continuous* interaction with the environment, I chose to investigate the development of skill in a tracking task in which this interaction is overt and measurable. Most of the confusion surrounding the issue of closed and open loop control has to do with the assumption that a system under

closed loop control will exhibit *discrete* feedback

corrections. This is not always the case however. Feedback

can also act in a continuous fashion in modulating action,

such that rather than being modified discretely, action is

modified continuously over time. Pilot data give support to

this contention (see appendix). As Powers (1973) has

pointed out:

"This (discrete model) is a natural first approximation

to describing a closed loop of causes and effects, but

it is incorrect ... the real organism behaves in a

smoothly continuous manner, with both responses and

stimuli continually changing and continually

interacting." (p. 42)

As yet, no-one has investigated relative timing in a

context in which there is a continuous interaction with the

environment, as there is in a tracking task. Coming out of

the theoretical framework associated with the motor program,

most of the studies on invariant relative timing have not

focussed on this relationship. By studying relative timing

in a tracking task, it was possible to gain an understanding

of the contribution that feedback makes in timing control.

The tracking paradigm was useful in that it required that

the subject continuously interact with the environment on

perceptual and motor levels, and it allowed precise

quantification of both stimulus and response patterns.

Five different but related forms of movement analysis

were used in this study in order to evaluate the performance

of the subjects: an error measurement indicating the
overall accuracy and precision of the subject (Root mean
squared error); a measure of the subject's ability to
reproduce the movement consistently during each trial
(within subject variability of the response profiles); a
lead lag index gained from a cross-correlation analysis that
represents the subject's ability to produce the response at
the correct time; an harmonic analysis that offers
information regarding the composition of the response; and
a calculation of the proportional duration of the time
between movement reversals.

The question of invariant relative timing was explored
using a training \ transfer paradigm in which subjects were
given extensive practice on tracking a specific waveform
(training) and then transferred to waveforms identical to
the training waveform in relative timing, but different in
overall duration. This was carried out under two
conditions: a **_pursuit tracking_** condition, in which both
stimulus and response information were visually available to
the subject, and an **_input blanking_** condition, in which
these sources of visual information were removed. Three
hypotheses were tested using this paradigm. Firstly,
following extensive practice on a given waveform, subjects
are capable of tracking, equally well, other waveforms which
have the same relative timing as the original waveform, but
different base frequencies. Secondly, when subjects are
required to reproduce (during input blanking) the original

and varied base frequency waveforms, their performance will
exhibit invariant relative timing between reversals in the
waveform. In addition, in order to test the hypothesis
(originally put forward in the pilot study) that a movement
is learned in terms of its component frequencies, subjects
were also transferred to two additional waveforms: the first
contained identical component frequencies to that of the
training waveform, but different phase angles, and the
second was an entirely new waveform (different frequency,
amplitude and phase relationships). If subjects learn a
movement in terms of component frequencies, then one would
expect to find a better performance on the waveform which
varied only the phase angles, than on an entirely new
waveform.

CHAPTER 2.

METHODS

Subjects

Six university students with no motor or vision deficits volunteered to participate in this study. None had had previous tracking experience. The subjects were right hand dominant and used this hand to move the joystick.

Task

Subjects were required to move a joystick which controlled a response cursor (point light display) on an oscilloscope screen. The subject's task was to follow a stimulus cursor (point light display) which appeared directly above the response cursor on the screen and moved in a series of horizontal movements across the screen. Subjects sat at a table with their right forearm comfortably supported. The oscilloscope screen was placed 50 cm in front of them at a visually subtended angle of 11.4 degrees. The subjects held the joystick between the index finger and thumb. The wrist pronated and supinated in the coronal plane while the joystick was being moved.

Apparatus

The joystick, an industry standard plotting joystick (Hughes Aircraft Company CONOGRAPHIC - 12 model 6110) was adapted for use in the experiment by bypassing internal

electronics within the joystick. The joystick was fed by a filtered 30 volt split power supply and connected to an analog to digital converter (Labmaster) with a 12 bit resolution, whose daughter board was resident in an IBM Microcomputer. The Labmaster gave digital values ranging from +2048 (+ 5 volts) to -2048 values (- 5 volts), while the voltage range of the joystick was approximately + 5 volts to -5 volts (zero volts being center). Values from the joystick were converted to oscilloscope displacement values ranging from 0 - 1000. The joystick was spring centered along the Y axis. The X axis had free displacement. Only X co-ordinate displacement was recorded. The potentiometer (a Bourns number 3852A-282-103A), which transformed joystick displacement into an electrical signal, had a resistance of 10,000 Ohms, and was linear (within one percent) throughout the full range of joystick movement. The joystick had a zero order control.

The joystick was tested for consistent linearity each day with the following procedure. A template was made in a range of 45 degrees with the left (0 degrees), the center (22 1/2 degrees), and the right (45 degrees) marked off. Each potentiometer that was used in the experiment was checked to verify that the displacement to the left of center was represented by an equal number of digital values as was the displacement to the right of center.

A computer generated stimulus was presented on the oscilloscope using a digital output equivalent to the

digital input of the joystick. A second analog signal was used to maintain 1 cm of vertical displacement between the stimulus and response cursors on the oscilloscope. Response values were sampled every four milliseconds.

The precision of the A/D interface between the joystick and the computer was tested using the following procedure. Fourteen locations across the range of the joystick were chosen at random. At each location, data was sampled at a rate of 250 Hz. for 4.096 seconds. At any of the fourteen locations, the range in the joystick never exceeded 4 digital values (or 0.008 volts) and was never less than 2 digital values (or 0.004 volts). The standard deviation varied from 0.3 to 0.47 digital values over the fourteen locations of the joystick. The resolution of the full range of the joystick was 1,000 digital values.

The range of the joystick was tested with the experimenter holding the joystick at rest for 40 seconds. With the joystick held at rest, the recorded range of the joystick was 0.7 millimeters. Thus any recorded movement less than 0.7 mm was not considered to be intentional movement.

Stimulus Waveforms

Subjects were given the following eight waveforms to track:

W1) The training waveform was given by the equation: $f(t) =$
    $A/2 + 240 \cos (\omega t + 3/2 \pi) + 120 \cos 2 (\omega t + 5/6 \pi) + 60$

cos 4 (ωt + 1/6 π). Where ωt represents the angular velocity and the phase angle is expressed in radians. The period of this waveform was 2048 ms with a base frequency of 0.5 Hz.

Four of the transfer waveforms were described by the same equation as the training waveform, however the base frequency was manipulated such that the following waveforms were created:

W2) the training waveform with a period of 3248 ms, and a base frequency of 0.3 Hz.

W3) the training waveform with a period of 2448 ms, and a base frequency of 0.4 Hz.

W4) the training waveform with a period of 1648 ms, and a base frequency of 0.6 Hz.

W5) the training waveform with a period of 1448 ms, and a base frequency of 0.7 Hz.

Waveform 6 was a transformation of the training waveform such that the phase angles of the frequency components were altered.

W6) This waveform is given by the equation: f(t) = A/2 + 240 cos (ωt + 3/2 π) + 120 cos 2 (ωt + 2/3 π) + 60 cos 4 (ωt + 1/4 π) with a period of 2048 and a base frequency of 0.5 Hz..

W7) This waveform was an entirely new waveform given by the equation: f(t) = A/2 + 230 cos (ωt + 3/2 π) + 130 cos 3 (ωt + 11/6 π) + 70 cos 4 (ωt + 2/3 π) with a period of 2048 ms and a base frequency of 0.5 Hz.. This waveform

was the same as the training waveform in that it had the same base frequency, the same number of component frequencies, and the same overall amplitude range. It varied from the training waveform in the amplitudes and phase angles of the component frequencies. These were varied in order to create a periodic waveform with the same overall amplitude range as the training waveform, and a different topology than the training waveform.

W8) This waveform was termed a random waveform because it never repeated itself. Its period was 40960 ms. It was made up of component frequencies with an amplitude range of 20 mm to 200 mm and frequencies ranging from 0.5 Hz to 2 Hz. The same waveform was given to subjects on each of the six transfer days. on each transfer day. Because this waveform had no cyclicity and thus no predictability, subjects were unable to use perceptual anticipation (Poulton, 1952) in tracking it.

Pursuit Tracking and Input Blanking

Each trial consisted of two conditions: pursuit tracking and input blanking. A trial began with 20 cycles of pursuit tracking in which both the stimulus and the response were presented on the screen, thus stimulus information, response information, and error information were available to the subject. Following this there were two cycles of tracking in which only the stimulus remained on the screen. This was used as a warning to the subject

that they would be beginning the input blanking stage of the trial. In the last portion of the trial, the input blanking phase, the subject was required to reproduce the waveform that had previously been tracked in the pursuit tracking phase, this being done in the absence of stimulus, response, and error information. The time to complete this phase of the trial was equivalent in duration to 12 cycles of the stimulus waveform. The middle 10 cycles of pursuit tracking and the middle six cycles of input blanking were sampled at 250 Hz.

Procedure

In order to motivate subjects to perform at their optimum level a prize was offered for the subject who achieved the best root mean squared (RMS) error score by the last day of the study. After each test trial, subjects were given feedback about their performance in the form of an overall RMS error score for that trial. Subjects were also asked informal questions about the phenomenological aspects of the tracking that they were asked to perform.

Over the course of 15 days, the subjects were given extensive practice in tracking the training waveform (W1). On each of the fifteen days of the study, their tracking performance was evaluated on this training waveform using various dependent measures. In addition, every third day the subject's tracking performance was assessed on the seven transfer waveforms. Each experimental session began with a

practice of 200 cycles of W1. These 200 cycles were divided into 4 blocks of 50 cycles. The time taken to track each block of cycles was approximately two minutes, after which subjects rested for a further two minutes before beginning the next block.

The fifteen days of this study were made up of nine training days and six transfer days. (See Table 1 for the layout of the experimental design.)

Training Days: On training days in addition to the practice component, subjects were given eight test trials on W1. Each trial consisted of twenty cycles of **pursuit tracking** in which both stimulus and response cursors were visible and ten cycles of input blanking in which neither the stimulus nor the response were displayed on the screen. Data was collected from the middle ten cycles of the pursuit tracking phase and from the middle five cycles of the **input blanking** phase. In the input blanking phase, data was collected for the duration of 6 stimulus cycles in order to ensure that 5 entire response cycles were collected. The sampling rate was 250 Hz.

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Table 1. Experimental Design

200 practice cycles on W1		8 test trials on:							
		W1	W2	W3	W4	W5	W6	W7	W8
1	**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**
2	X	X							
3	X	X							
DAYS **4**	**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**
5	X	X							
6	X	X							
7	**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**
8	X	X							
9	X	X							
10	**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**
11	X	X							
12	X	X							
13	**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**
14	X	X							
15	**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**

One test trial consisted of 20 cycles of pursuit tracking followed by 25 seconds of input blanking. Transfer days are highlighted.

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Transfer Days: On transfer days in addition to the practice component, subjects were given one trial of each of the eight waveforms (W1 - W8). One trial of each waveform

was comprised of the two phases described above i.e. **pursuit tracking** and **input blanking**.

Data Analysis

Root mean squared error (RMS Error) was calculated on the *pursuit tracking* data in order to determine response accuracy. Poulton (1974) defines RMS error as the square root of the sum of the squares of the error at each sampling interval, divided by the number of sampling intervals. It is given by the equation: RMSE = [Σ (s-r)^2/ p]$^{1/2}$, where s is the stimulus value at time interval t, r is the response value at time interval t, and p is the number of intervals that the response is sampled over.

RMS error has been reccommended by Poulton as the best measure for evaluating the "overall *adequacy* of tracking" (1974, p.38). A decrease in the value of RMS error scores indicates that the subject has become more accurate and precise in tracking, and thus is indicative of learning (Franks, Wilberg & Fishburne, 1985; Poulton, 1974).

A computer program was written to calculate the RMS error for the pursuit tracking performance of this study. In order to determine the lowest possible RMS score with the present equipment, data were collected with the joystick at rest for the duration of two cycles of the stimulus waveform (1024 data points). The mean over the 1024 data points was calculated. A data file was then created in which this mean value was substituted for all 1024 stimulus values. The RMS

program was then run on this data file producing an RMS

value of 0.3 data points or 0.45 mm.

RMS Error was also calculated on the *input blanking*

data in order to compare performance on the various

waveforms during input blanking. Each cycle of input

blanking was normalized in terms of its overall duration,

and in terms of its spatial symmetry. This was done in

order to account for the temporal and spatial drift that can

occur when neither stimulus nor response are visible to the

subject (Vossius, 1965). The normalized response was then

compared to the stimulus in such a way as to determine the

lowest RMS value for that cycle. This was achieved by

shifting the response in both the forward and backward

directions for a total of 20 ms by intervals of 4 ms.

The *Variability* of each subject's response was

calculated within each trial for the pursuit tracking phase

based on a procedure from Franks, Wilberg & Fishburne

(1982). The displacement-time curves (ten from each trial)

were superimposed upon one another in order to calculate a

within trial variability score. At each of the 512 sampling

intervals, a standard deviation (sd) of the ten response

displacements was calculated using the following equation:

S.D. = [Σ (Mean$_r$ - r)^2 / 10]$^{1/2}$, where r is the response

at a given time interval and p is the number of intervals at

which r is sampled. The standard deviation values were

plotted against time yielding a profile of the within

waveform variability for a given subject on a given trial.

The mean of the 512 sd's was calculated and this was used as an index of the within subject variability (v) for a given trial.

Variability measures have been used in motor learning and tracking studies to evaluate skill acquisition. Many studies have found that a subject's response becomes more consistent as a result of practice, and use of this particular measure has reflected this phenomenon in recent studies. (e.g. Franks, Wilberg, & Fishburne, 1982; Glencross, 1979).

A test was made in order to determine the lowest variability score possible given any error in the system as a whole, including the variability program itself, the A/D converter, and the joystick. Data collected during ten cycles in which the joystick remained at rest. The joystick remained in the same location for each of the ten cycles. The duration of each cycle was 2.048 seconds and the digital values (sampled at 250 Hz) that were collected during each cycle were compiled into displacement time profiles which were then superimposed upon one another. From these values, standard deviation values were calculated at each point in time. The range of these standard deviation values was between 0 and 1 digital values. The mean of these standard deviation values was 0.3 digital values.

Lead-lag index was used to determine the extent to which the subject led or lagged the stimulus during pursuit tracking. A cross-correlation coefficient was calculated

using the stimulus and the response waveforms (each composed of 512 points), with the stimulus being held constant and the response signal being advanced in time by intervals of ten milliseconds. For each advancement of the response signal a Pearson product-moment correlation coefficient between stimulus and response was calculated. The time at which the correlation between stimulus and response was greatest was used to determine the lead or lag of the response with respect to the stimulus.

The lead-lag index has been used to evaluate the lag of the response relative to the stimulus during tracking (Bennett, 1957 (cited in Franks, 1982); Franks, 1982; Franks & Wilberg, 1982). The limitation of this measure is that it only reflects the average lead or lag, rather than the specific location in the waveform at which the subject was leading or lagging (Poulton, 1974).

Harmonic analysis was used to analyze the response waveforms from the input blanking phase into component frequencies. The Harmonic analysis yielded the following information: i)the component frequencies of the response. ii) the amplitude values of these component frequencies. iii) the phase angle values of these component frequencies. iv) the period of the waveform.

Harmonic analysis was used to determine the frequency, amplitude, and phasing of a cyclic waveform. Bernstein (1967) was among the first to use harmonic analysis in the study of human movement. In the early 1900's, he performed

experiments in which he filmed subjects performing various movements. The movement patterns of the various joints were then analyzed into component frequencies. More recently this analysis has been used by Green (1971) on RT data, by Franks and Wilberg (1982) in tracking, by Marteniuk & Romanow (1983) on arm movement trajectories, and by Richardson and Pew (1968) in measuring stabilometer performance. In the present study, Harmonic analysis was used in the input blanking condition to determine the composition of the response waveform. The phase angles of the frequency components of the response were compared with those of the stimulus in order to determine whether the relative timing of the response was equivalent to that of the stimulus. The period of the response was compared with the period of the stimulus in order to determine whether the overall duration of one cycle of the response waveform was the same as the overall duration of one cycle of the stimulus waveform.

The harmonic analysis was calculated based on a method described in Lowry and Hayden (1951 pp 324 - 328). The periodicity of the waveform (period $= 2\pi$) was determined using an autocorrelation. This waveform was divided into p equal units and each of these points were labelled x0, x1, x2, ... xp, with their corresponding ordinate values being y0, y1, y2, ... yp. The trapezoidal rule of integration was applied over the period yielding the following equations: 1) $a_0 = 2/p \, \pi \, y_r$ 2) $a_n = 2/p \, \pi \, y_r \cos nx_r$

$$3)\ b_n = 2/p\ \pi\ y_r\ \sin\ nx_r$$

Equation 2 gave the harmonic coefficients of the cosine

component of the waveform, while equation 3 gave the

harmonic coefficients of the sine component of the waveform.

The entire waveform was described by the equation:

$$f(t) = A_o/2 + \pi\ A_n\ \cos\ n\omega t + B_n\ \sin\ n\omega t$$

This equation was expressed in terms of a cosine function:

$$f(t) = A_o/2 + \pi\ C_n\ \cos\ (n\omega t - \phi_n)\quad \text{where}\ Cn = A_n^2 + B_n^2$$

ϕ_n represented the phase angle values which provided the

necessary timing relationship among various harmonic

components. These phase angle values were determined using

the following equation: $\tan\ \phi_n = B_n/A_n$.

In order to test the accuracy of the harmonic analysis,

the stimulus waveform itself was analyzed into component

frequencies. These data were then resynthesized into a

waveform which was compared to the original waveform by

calculating the RMS error between the two waveforms. This

produced an RMS error of 1.8 mm.

Interval Durations were calculated on the response

waveforms that the subjects generated during input blanking.

Each response cycle was divided into intervals by

calculating the time between adjacent reversals. A program

was developed in order to aid the experimenter in precisely

marking these reversals. The displacement time profile of

each cycle was presented on a computer screen. The

experimenter went through each response cycle marking the

point of each reversal. The computer then recorded the X

and Y coordinates of that point. X represented the temporal dimension. Y represented the spatial dimension. In order to calculate an interval duration, the X coordinate value at the beginning of the interval was subtracted from the X coordinate value at the end of that interval. The interval duration was then expressed as a proportion of the overall duration of the entire cycle by dividing the interval duration by the overall duration of the cycle in which the interval occurred.

Interval Displacements were calculated using the same procedure as that used for the interval durations. In order to calculate an interval displacement, the Y coordinate value at the beginning of the interval was subtracted from the Y coordinate value at the end of that interval. The interval displacement was then expressed as a proportion of the maximum displacement by dividing the interval displacement by the maximum displacement of the cycle in which the interval occurred.

Statistical Analysis

Pursuit Tracking: RMS error data were subjected to a Waves (8) by Days (6) ANOVA with pre-planned orthogonal contrasts and repeated measures on both factors. Contrasts were planned for both the days factor (trend analysis) and the waves factor. The seven contrasts performed on the waves factor were as follows:

1) The training waveform (W1) was contrasted with the varied

speed waveforms (W2, W3, W4, W5) pooled together.

2) The slow waveforms (W2 & W3) were compared with the fast waveforms (W4 & W5).

3) The slowest waveform (W2) was contrasted with the second slowest waveform (W3).

4) The fastest waveform (W5) was compared with the second fastest waveform (W4).

5) The waveform in which the phase angles of the frequency components were altered (W6) was contrasted with the entirely new waveform (W7).

6) W1, W2, W3, W4 & W5 pooled were contrasted with W6 & W7 pooled.

7) The random waveform (W8) was contrasted with W1-W7 pooled.

Input Blanking: Both the **interval displacement** and **interval duration** data from day fifteen were subjected to a waves (5) by intervals (5) by cycles (3) repeated measures ANOVA with trend analysis on all factors. The waveforms used in this analysis were waves one through five.

CHAPTER 3.

RESULTS

Part One - Pursuit Tracking

Subjects were given extensive practice daily in tracking a specific periodic waveform (the training waveform, w1) which had a base frequency of 0.49 Hz.. Under investigation was the question "would subjects be able to perform equally well on waveforms which maintained the relative timing of the training waveform, but were transformed in terms of their base frequency?" In order to answer this question, pursuit tracking performance was evaluated using three dependent measures: **RMS error;** **within subject variability;** and **lead-lag index** (calculated using a cross-correlation function).

I.   RMS Error

RMS data were subjected to a Waves(8) by Days(6) ANOVA with planned orthogonal contrasts and repeated measures on both factors. Contrasts were planned for both the days factor (trend analysis) and the waves factor.
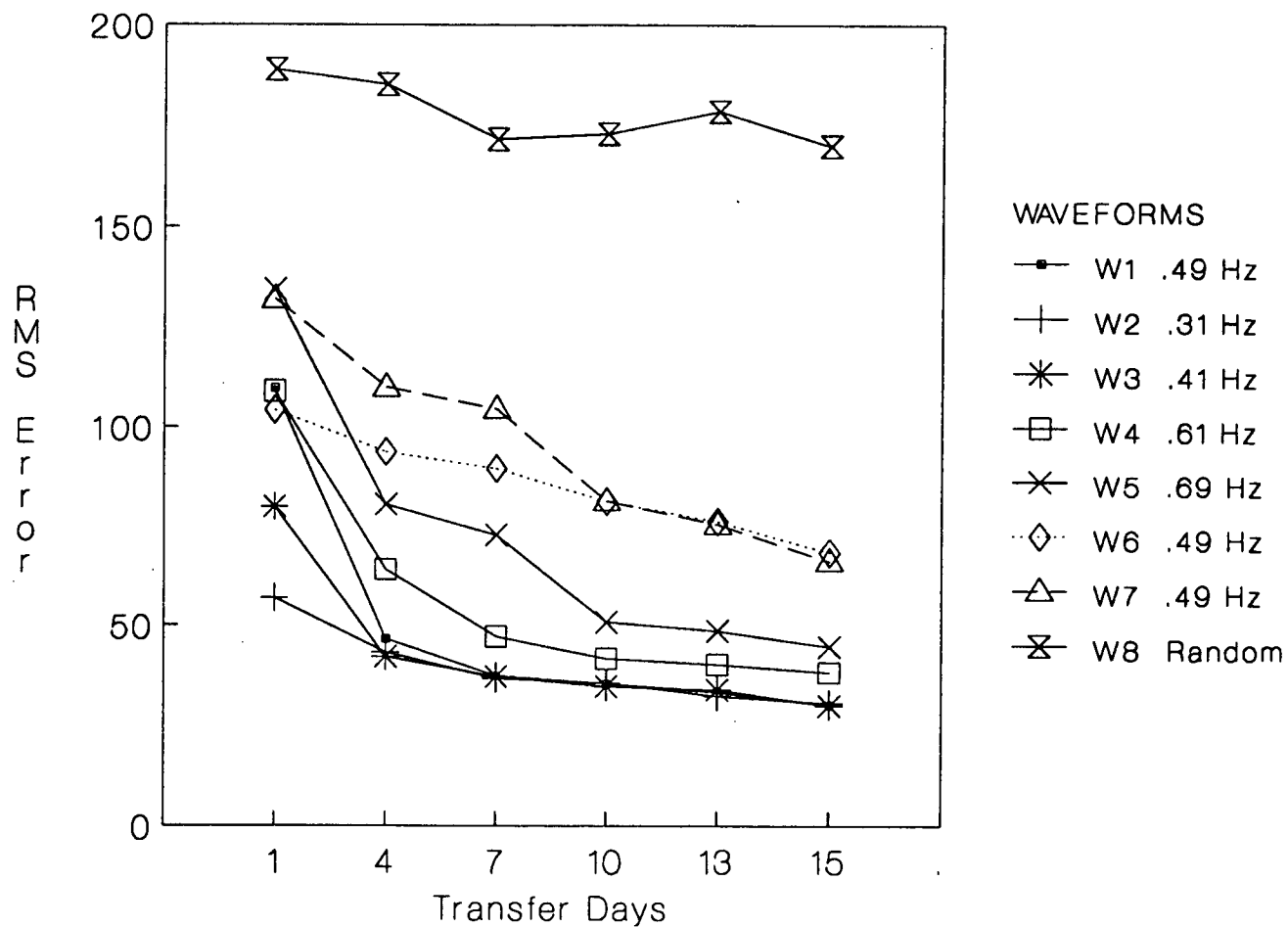
A) Day 15

Of the RMS data, the first to be considered will be the RMS values on the last day, **day 15.** Seven planned orthogonal contrasts were performed on the RMS values of all eight waveforms from day 15:

Figure 1.

Root Mean Squared Error as a function of practice.

RMS ERROR AS A FUNCTION OF PRACTICE

RMS Error in units of 1/10 mm

In the **first contrast**, RMS values on the training wave (w1) were compared with the varied speed waves (w2, w3, w4, w5) pooled. This contrast was significant $F(1,5)=32.3$, $p=0.002$. Subjects, therefore, performed significantly worse on various speeds of the training waveform (M = 36) considered together, than they did on the original itself (M = 30). However, in taking a closer look at the RMS data on this last day (see Figure 1), it is evident that the slower waves had the same RMS value as the original wave. Thus the original and slower waves were the same as each other but different than the faster waveforms; subjects performed as well on the two slower waveforms (on which they had minimal practice) as they did on w1, on which they had extensive training

The **second contrast** compared w2 and w3 (the slow waves) with w4 and w5 (the fast waves). The slow waves (M = 30.5) were found to be significantly different than the fast waves (M = 41.5) $F(1,5)=8.7$, $p=0.032$, meaning that subjects performed significantly better on the slow waves than they did on the fast waves (as measured by RMS error).

The **third contrast** compared w2 (the slowest wave) with w3 (the second slowest wave). There were no differences in RMS values on the two waveforms $F(1,5) < 1.0..$

The **fourth contrast** compared w4 with w5. RMS values on w5, the fastest waveform (M = 45), were significantly higher than those on w4, the second fastest waveform (M = 38), $F(1,5)=8.0$, $p=0.036$.

The **fifth contrast** compared w1 - w5 pooled (the varied speed waveforms) with w6 & w7 pooled (the constant speed waveforms). RMS values on the first group were significantly lower that RMS values on the second group $F(1,5)=66.7$, $p<0.001$. Thus subjects performed more accurately while tracking the waveforms that varied only in base frequency (w1 - w5) than while tracking the waveforms that varied the phase relationships among the component frequencies (w6) or varied the component frequencies themselves (w7). As can be seen in Figure 1, not only did subjects perform better on the training wave (w1) and the two slower waves (w2 & w3) than they did on w6 and w7, they also performed better on the two faster speeds, w4 & w5, which had base frequencies of 0.61 and 0.69 Hz respectively, than they performed on W6 and w7, which both had base frequencies of 0.49 Hz.

The **sixth contrast** compared w6 with w7. RMS values on W6 and W7 were not different $F(1,5)=0.1$, $p < 1.0$, indicating that subjects do not find w6 (a waveform that contains the same component frequencies as the training waveform) any easier to track than w7 (an entirely new waveform).

The **seventh contrast** compared w8 (the random waveform) with w1 - w7 (the periodic waveforms) pooled. As expected RMS values on w8 were significantly higher than those on w1 - w7 pooled $F(1,5)=497.2$, $p<0.001$.

Table 2
Waves * Days Interactions: RMS Error.

SOURCE	SS	SS%	DF	MS	F	P
W * D	26,944.1	100.0%	35, 175	769.8	7.15	0.001
W_{c1} * D_L	453.4	1.7%	1, 5	453.4	4.04	0.101
W_{c1} * D_Q	898.6	2.9%	1, 5	898.6	6.61	0.050
W_{c2} * D_L	6510.5	24.2%	1, 5	6510.5	104.5	0.001
W_{c2} * D_Q	1507.7	5.6%	1, 5	1507.7	11.6	0.019
W_{c3} * D_L	525.7	1.9%	1, 5	525.7	30.17	0.003
W_{c3} * D_Q	452.7	1.7%	1, 5	452.7	31.47	0.002
W_{c4} * D_L	774.7	2.9%	1, 5	774.7	6.83	0.047
W_{c4} * D_Q	0.4	0.0%	1, 5	0.35	0.00	0.948
W_{c5} * D_L	85.9	0.3%	1, 5	85.9	0.39	0.560
W_{c5} * D_Q	3698.4	13.7%	1, 5	3698.4	35.9	0.002
W_{c6} * D_L	1992.8	7.4%	1, 5	1992.8	6.56	0.051
W_{c6} * D_Q	94.8	0.4%	1, 5	94.8	0.27	0.625
W_{c7} * D_L	4905.7	18.2%	1, 5	4905.7	17.8	0.008
W_{c7} * D_Q	908.8	3.4%	1, 5	908.8	4.21	0.095

c_1 = contrast one D_L = days linear D_Q = days quadratic

B) Day 1 through Day 15

In order to determine the differences in the rates of improvement amongst the various waveforms, the waves by days interactions will be examined. Table 21 gives a detailed account of these interactions. Only the significant interactions will be addressed in the text of the results.

The **interaction** of **contrast 2** (the slow waves compared to the fast waves) with **days linear** was significant $F(1,5)=104.5$, $p=0.001$ indicating that the fast waves improved at a faster rate than the slow waves. This difference in slope between the fast and slow waves is also evident in Figure 1, but appears to be primarily due to the steeper slope from day 1 to day 10. The **interaction** of **contrast 2** with **days quadratic** was significant $F(1,5)=11.6$, $p=0.019$ revealing that the quadratic component of the days effect was different between the slow and fast waves. The stronger quadratic component of the days effect for the fast waves is apparent in Figure 1. As can be seen, there was a greater change in slope over days for the fast waves than there was for the slow waves.

The **interaction** of **contrast 5** (w1 - w5 pooled compared to w6 & w7 pooled) with **days quadratic** was significant $F(1,5)=35.9$, $p=0.002$. It is apparent from Figure 1 that the days effect on w1 through w5 has a strong quadratic component. On these waves there is a large drop in RMS from day one to day four. W6 and w7 show no such drop. Their progress is fairly linear from day one to day fifteen.

The **interaction** of **contrast 7** (w8 compared to w1 - w7 pooled) with **days linear** was significant $F(1,5)=17.8$, $p=0.008$. Over the fifteen days, subjects' performance showed greater improvement on the periodic waveforms than on the random waveform; as Figure 1 illustrates, the random waveform (w8) had a more shallow slope than did the periodic waveforms (w1 - w7).

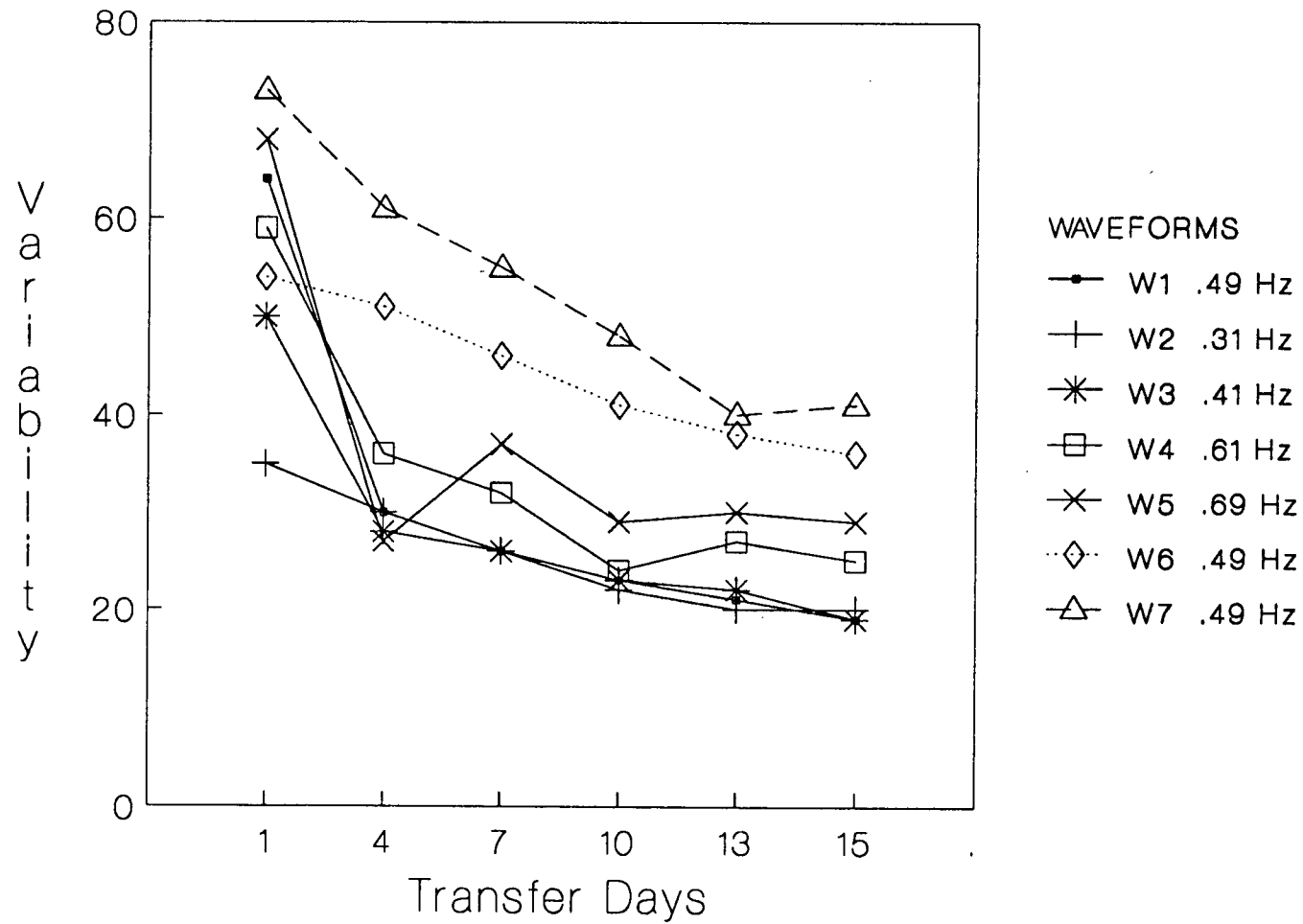## II. Within Subject Variability

Variability scores were subjected to a repeated measures ANOVA on all waveforms (w1, w2, w3, w4, w5, w6, w7, and w8) from day 15, using the same planned orthogonal contrasts that were used in the RMS ANOVA. (Variability scores were calculated by taking the mean of 512 standard deviation values from the displacement time profiles of 10 cycles of pursuit tracking.) Results from the ANOVA on the variability data paralleled closely the results from the ANOVA on the RMS data (see Table 3). The only contrast that deviated from this pattern was **contrast 2** in which the slow waves were contrasted with the fast waves. In the case of the variability data this contrast was not significant $F(1,5)=4.2$, $p=0.095$. Thus the slow waves are not significantly different from the fast waves on the variability measure.

As Figure 2 illustrates, subjects' responses on all eight waveforms were more variable early in learning (day 1) than they were later in learning (day 15). In considering

Figure 2.

Mean of 512 standard deviation values from the displacement

time profiles of 10 cycles of pursuit tracking for 7

waveforms over 6 transfer days.

VARIABILITY AS A FUNCTION OF PRACTICE

Variability in units of 1/10 mm

both the variability and the RMS results, it is evident that as subjects became more accurate they also became less variable in their response.

Table 3   ANOVA Table Variability
Planned Contrasts   Day 15

CONTRAST	F	DF	P
1) W1 vs W2-W5	20.29	1, 5	0.006
2) W2 & W3 vs W4 & W5	4.23	1, 5	0.095
3) W2 vs W3	1.66	1, 5	0.254
4) W4 vs W5	8.87	1, 5	0.031
5) W1-W5 vs W6 & W7	26.23	1, 5	0.004
6) W6 vs W7	2.03	1, 5	0.213
7) W8 vs W1-W7	169.47	1, 5	0.001

III. Lead-Lag Index

As is evident from Figures 3 and 4, on day one the subjects' responses lagged behind the stimulus during the pursuit tracking of all waveforms (w1, w2, w3, w4, w5, w6, w7, and w8). On the faster waves, the responses lagged behind the stimulus by the greatest amount. Over the fifteen days of training, subjects' responses on all five of the various speed waveforms (w1 - w5) moved nearer the zero lag point. By day 15, the responses on w1, w2, and w3 (the training and slower waveforms) were at the zero lag point. Responses on the two faster waves ,w4 and w5, lagged the stimulus by 7 and 5 milliseconds on day 15.

The variability of the lag of the subjects' responses for all waveforms (Figure 5) decreased as learning progressed, making the mean lag values from day 15 more

Figure 3.

The lead-lag index of the subjects' responses relative to

the stimulus as a function of practice for w1 - w5.

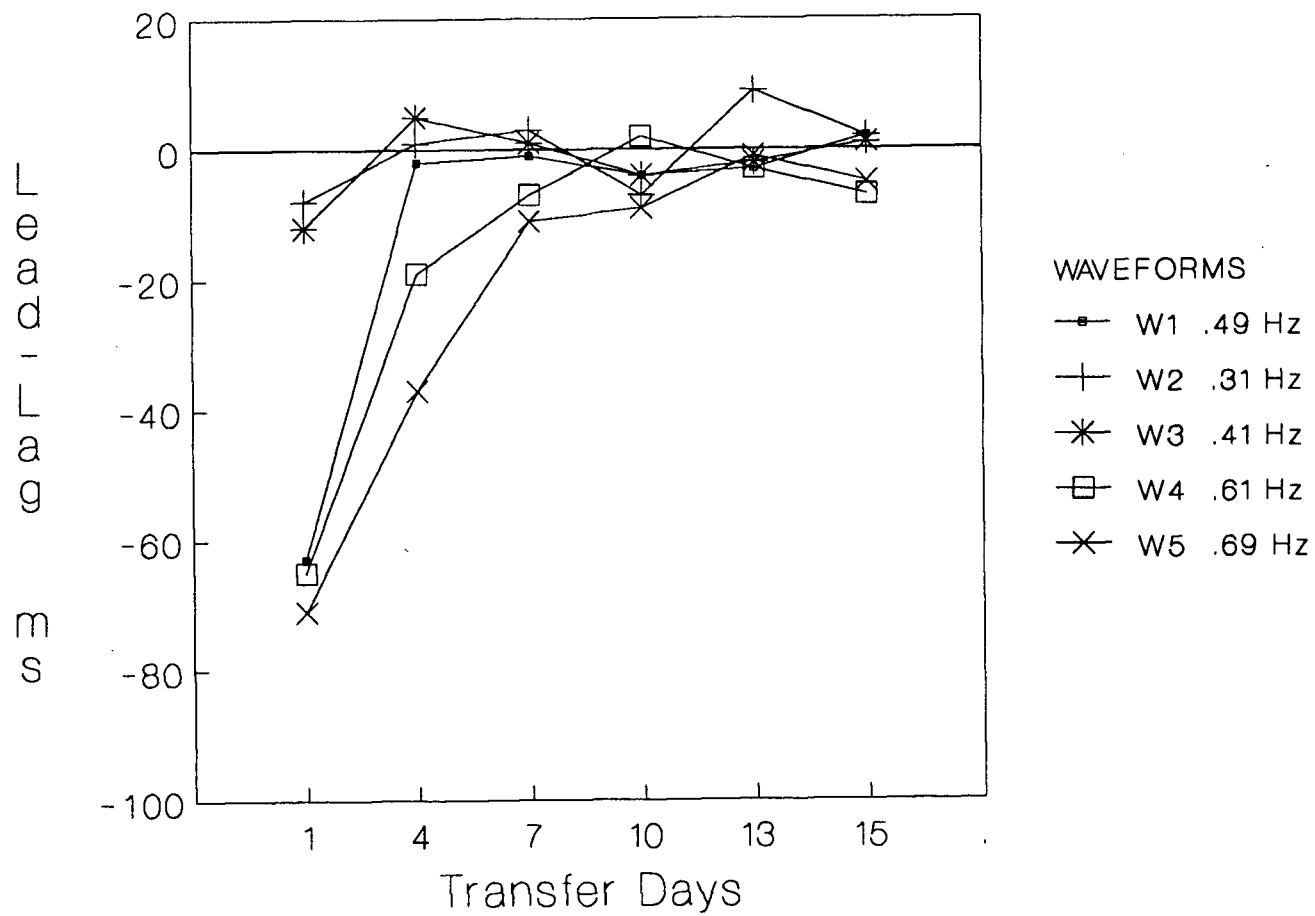LEAD-LAG AS A FUNCTION OF PRACTICE

Figure 4.

The lead-lag index of the subjects' respones relative to the
stimulus as a function fo practice for w6 - w8.
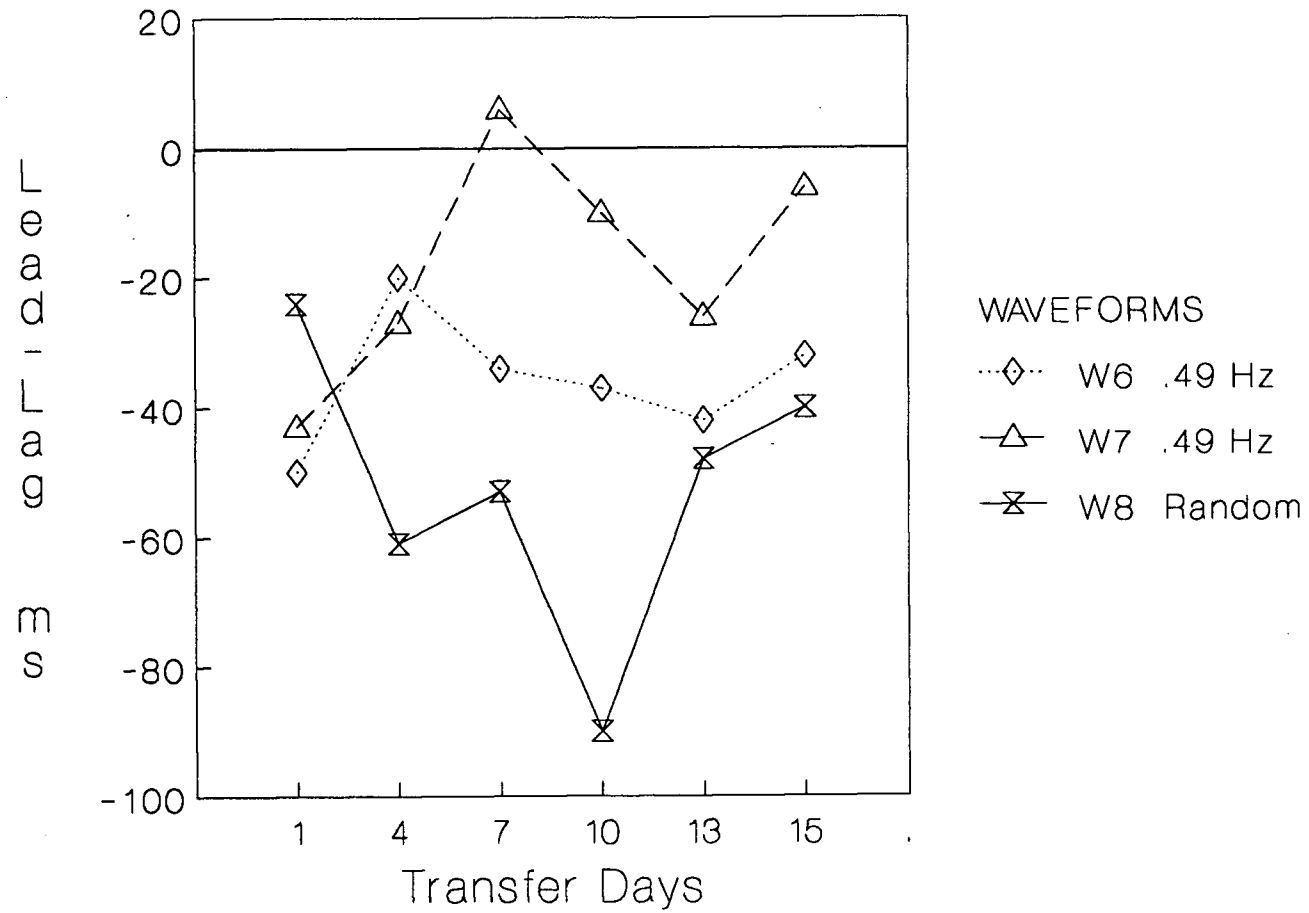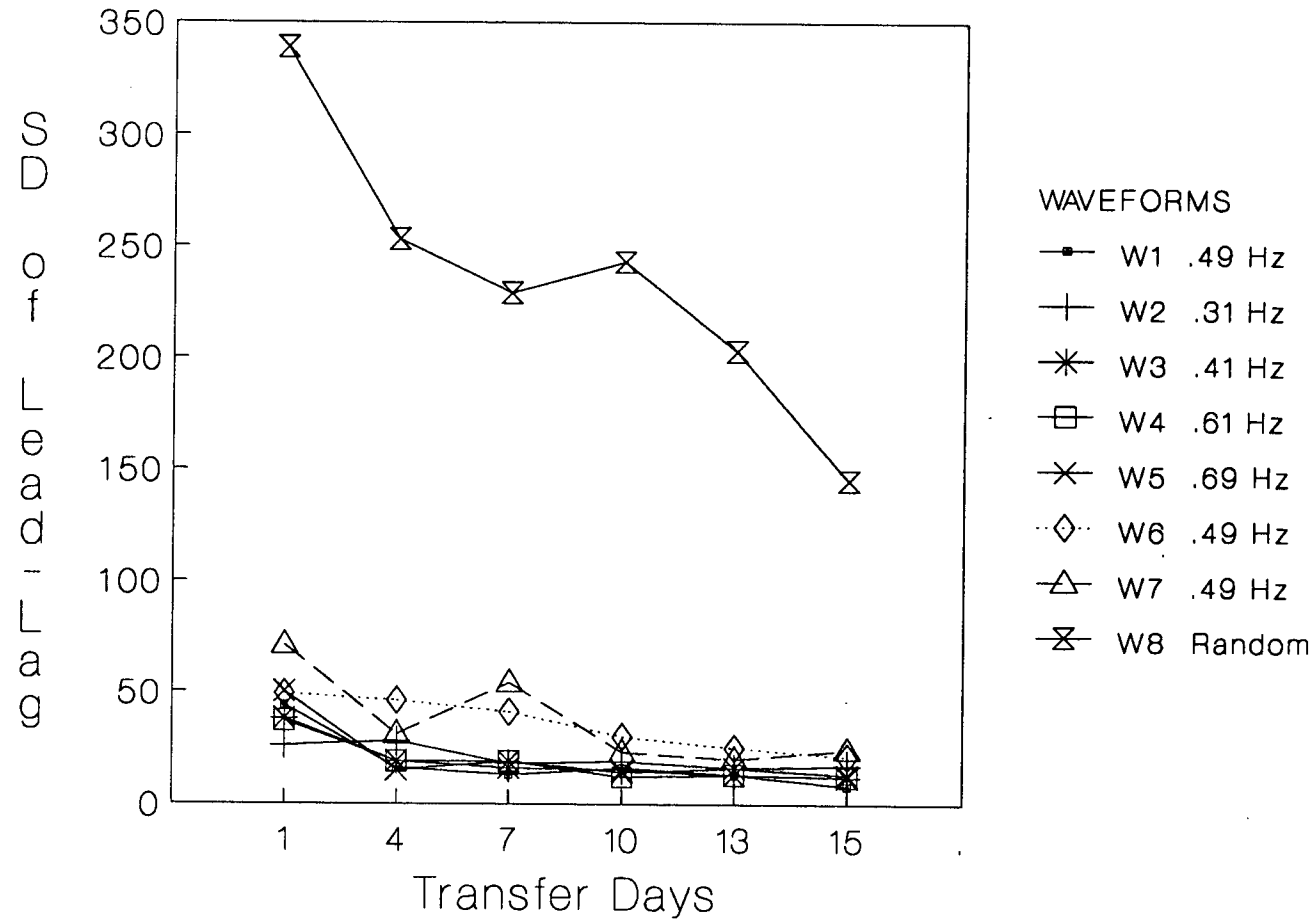
LEAD-LAG AS A FUNCTION OF PRACTICE

Figure 5.

The standard deviations of the lead-lag index of the

subjects' responses relative to the stimulus for w1 - w8.

VARIABILITY OF LEAD-LAG SCORES

reliable than the mean values from day 1. Responses on the random waveform exhibited much greater variability throughout and showed the greatest decrease in variability over the fifteen days of training.

Part Two - Input Blanking

Several dependent variables were used in order to evaluate performance on the input blanking data on Day 15.

I) **Interval durations** expressed as a proportion of the overall duration (an index of relative timing).

II) **Interval displacements** expressed as a proportion of the maximum displacement (an index of relative displacement).

III) **Cycle duration** or **period** of the response waveforms from w1 - w7 (the periodic waveforms).

IV) **Root Mean Squared Error.**

V) **Frequency composition** of the response waveforms (calculated using Harmonic analysis).

VI) **Kinematic profiles** of the response waveforms.

I. Interval Durations

Interval durations from the input blanking data (day 15) were analyzed in order to determine whether subjects maintained a consistent **proportional** duration across repeated instances of a given movement interval. In this experiment, a movement interval was defined as the time from one reversal to an adjacent reversal (or stop) of the

Figure 6.

Waveforms by intervals interaction for proportional interval
duration data.

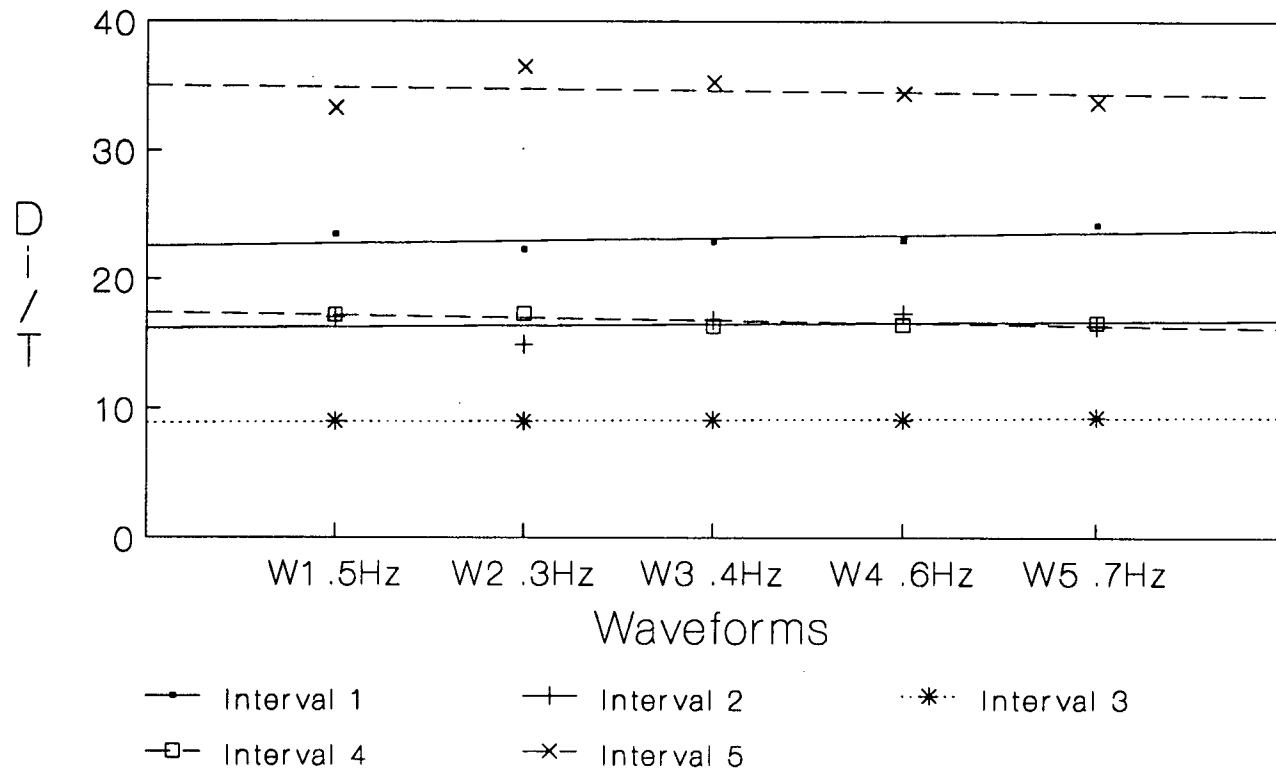# Di/T as a function of Waveforms
(collapsed over cycles)

Figure 7.

Intervals by cyles interaction for proportional interval

duration data.
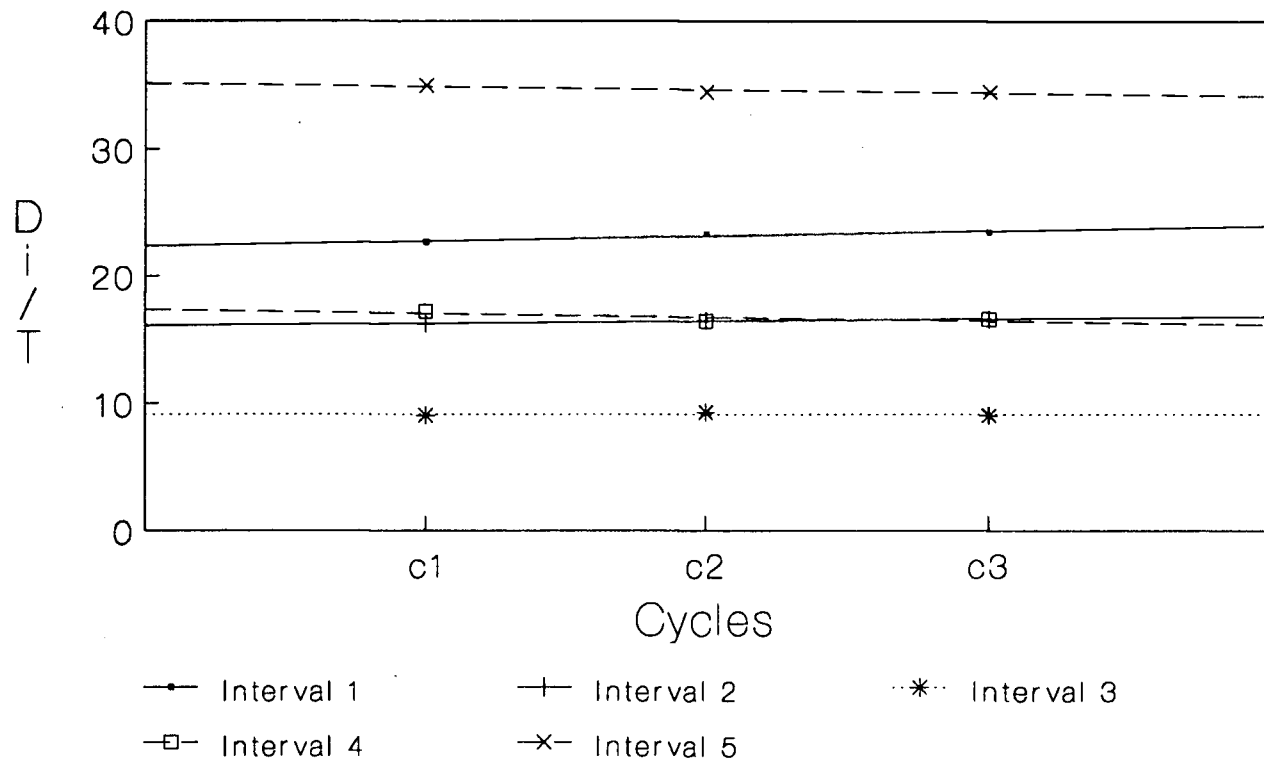
Di/T as a function of Cycles
(collapsed over waveforms)

Figure 8.

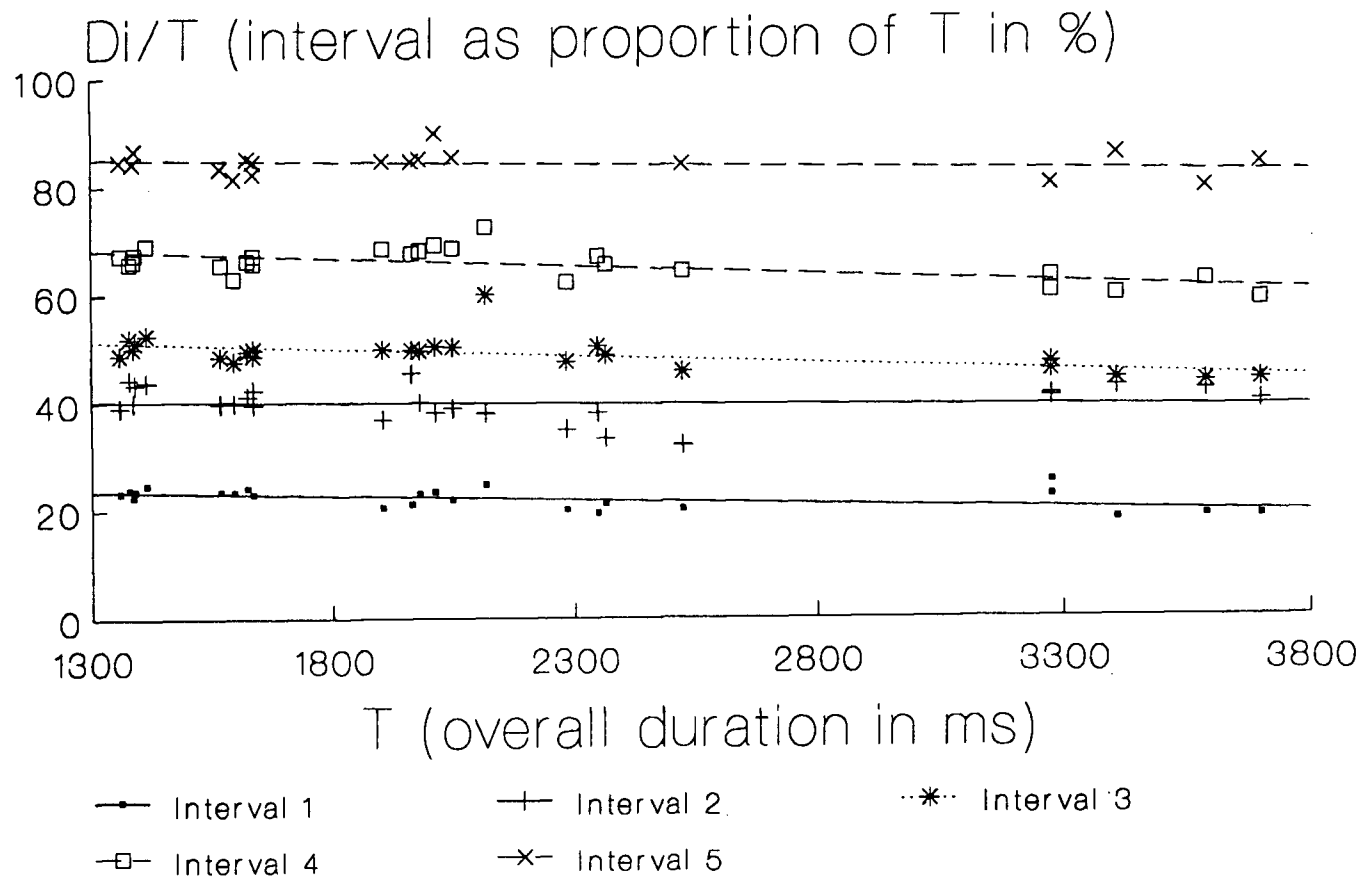Proportional interval durations as a function of overall

duration for subject 2.

Subject 2   Day 15   Waves 1 - 5

Di/T (interval as proportion of T in %)

T (overall duration in ms)

Interval 1   Interval 2   Interval 3
Interval 4   Interval 5

movement pattern. Each of the stimulus waves 1 to 5 contained five such intervals with proportional durations of 21%, 17%, 10%, 16% & 35% of the overall duration. The proportional duration of a response interval was calculated by dividing the interval duration by the overall duration of that cycle in which the interval occurred.

Table 4   ANOVA Table Interval Durations

SOURCE	F	DF	P
WAVES	1.58	4, 16	0.227
INTERVALS	95.60	4, 16	0.001
WI	0.79	16, 64	0.693
WI(1,1)	0.44	1, 4	0.544
WI(1,2)	0.06	1, 4	0.821
WI(1,3)	0.07	1, 4	0.805
WI(1,4)	0.54	1, 4	0.504
CYCLES	0.82	2, 8	0.475
WC	1.33	8, 32	0.266
IC	0.89	8, 32	0.534
WIC	0.95	32, 128	0.557

The proportional interval durations on day 15 were subjected to a waves(5) * intervals(5) * cycles(3) repeated measures ANOVA with trend analysis on all factors. The waves main effect (see Table 4) was non-significant $F(4,16)=1.58$, p=0.23, as expected. Because all interval durations were taken as proportions of the overall duration, when the data were collapsed over the five intervals, the mean interval duration became in all cases 20% of the total duration. A non-significant main effect was expected no matter what the actual interval durations values. For this reason, it was the waves by intervals interaction that was of concern in evaluating the relative timing hypothesis (see Introduction p.2). The waves by intervals interaction was

not significant F(16,64)=0.79, p=0.693. The **proportional**
interval durations, therefore, appear to be invariant. (For
a graphical representation of the waves by intervals
interaction see Figure 6). In addition, both the
waves(linear) and waves(quadratic) by intervals interactions
were non-significant (in both cases p > 0.50), thus lending
support to the invariant relative timing hypothesis.

The cycles main effect F(2,8)=0.82, p=0.475 was non-
significant indicating that when the proportional interval
duration data were collapsed over waveforms and intervals,
the mean proportional interval durations from the three
cycles were the same.

The waves by cycles interaction was non-significant
F(8,32)=1.33, p=0.266 indicating that when the proportional
interval duration data were collapsed over intervals, the
differences between waveforms (actually equality) was
constant over the three cycles.

The intervals by cycles interaction was non-significant
F(8,32)=0.89, p=0.534 indicating that when the proportional
interval duration data were collapsed over waveforms, the
differences among the five intervals under each of the three
cycles were constant over the three cycles. For a graphical
representation of this interaction see Figure 7.

Although it has been suggested (Gentner, 1987) that it
is necessary to calculate regression lines for each subject
for each interval, this is not necessary provided that the
within subject variability is low enough. (For an example

of regression lines fitted to the data of an individual

subject see Figure 8). In the present study, the within

subject variability (coefficient of variation) was

calculated and is presented in the following table:

Table 5   Intra-individual Variability for Interval Durations across the Five Waveforms.

	SD_{15}	V
Interval 1	2.4	0.10
Interval 2	1.7	0.10
Interval 3	1.4	0.15
Interval 4	1.7	0.10
Interval 5	2.6	0.07

SD = standard deviation over fifteen cycles
V = coefficient of variation

II. Interval Displacements

The interval displacement data were analyzed using a

three way ANOVA which was identical to that used on the

interval duration data. The dependent measure was a

relative interval displacement. In a given cycle, each

interval displacement was divided by the maximum

displacement that occurred in that cycle, thus giving an

interval displacement expressed as a proportion of the

maximum displacement. The five proportional interval

displacement values for the stimulus (or criterion) were

50%, 20%, 9%, 38%, 100%.

Table 6   ANOVA Table   Interval Displacements

SOURCE	F	DF	P
WAVES	0.50	4, 16	0.737
INTERVALS	412.52	4, 16	0.000
WI	0.56	16, 64	0.899
WI(1,1)	0.89	1, 4	0.340
WI(1,2)	0.17	1, 4	0.705
WI(1,3)	1.29	1, 4	0.319
WI(1,4)	2.33	1, 4	0.202
CYCLES	0.03	2, 8	0.967
WC	0.97	8, 32	0.476
IC	0.37	8, 32	0.931
WIC	1.63	32, 128	0.030
			(0.075)*

* Huynh-Feldt adjusted p value

Table 7   Intra-individual Variability for Interval Displacements across the Five Waveforms.

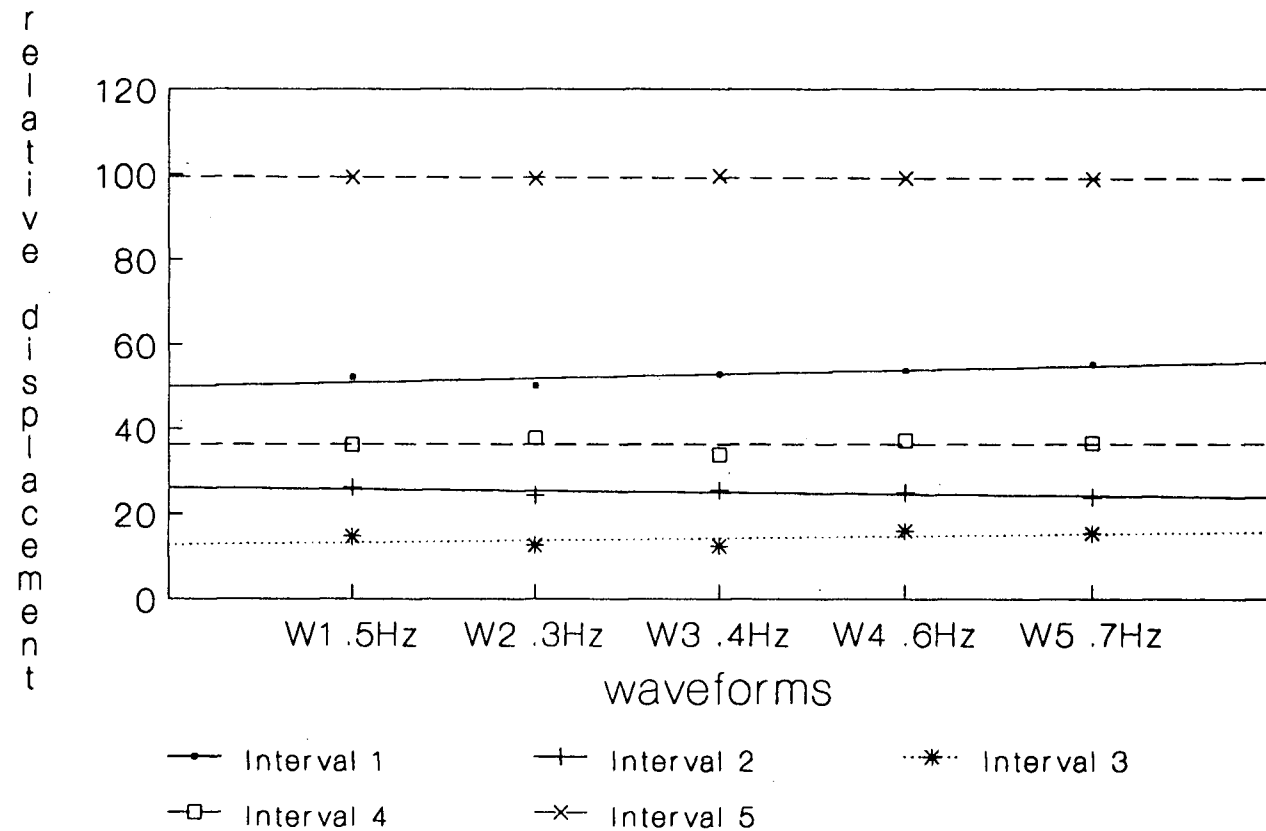|	SD_{15}	V
Interval 1	5.5	0.10
Interval 2	4.4	5.67
Interval 3	4.3	3.00
Interval 4	4.2	0.12
Interval 5	5.7	0.06

SD = standard deviation over fifteen cycles
V = coefficient of variation

The interval displacement data (see Table 6) parallel closely the interval duration data. (For a graphical representation of the waves by intervals interaction for the interval displacement data see Figure 9). The interval displacement and interval duration data were different only in the within subject variability (indicated by the error term). The variability of the displacement data was larger

Figure 9.

Waveforms by intervals interaction for relative interval

displacement data.

Relative Displacement as a Function
of Waveforms (collapsed over cycles)

57

than that of the duration data. However the displacement
data values were larger than the duration data values.
Duration data values were limited to a range of 100 points,
whereas, displacement data interval values were limited to a
range of 230 points.

III. Period

On all waveforms (w1 - w7) subjects reproduced a
response waveform whose period was longer than the stimulus
period (see Figures 10 & 11). For the slower waveforms on
day one, the subjects reproduced waveforms whose period was
longer than the stimulus period, by 73 ms for w2, and by 166
ms for w3. By day 15, the periods of the response waveforms
of w2 and w3 were longer than the stimulus periods by 327
and 248 ms respectively.

On the faster and training waveforms, subjects became
more accurate in reproducing the stimulus period with
practice. As with the slower waveforms, response periods on
the faster and training waveforms were longer than the
stimulus periods on day one. However with practice, these
response periods became shorter such that by day 15 the
response periods of w1, w2 and w3 were closer to those of
the stimulus periods than they had been on day 1.

In the case of w6 and w7 (just as for w1 - w5) the
periods of the response waveforms were always longer than
those of the stimulus. Thus during input blanking, subjects

Figure 10.

Mean period over five cycles of input blanking w1 - w5.
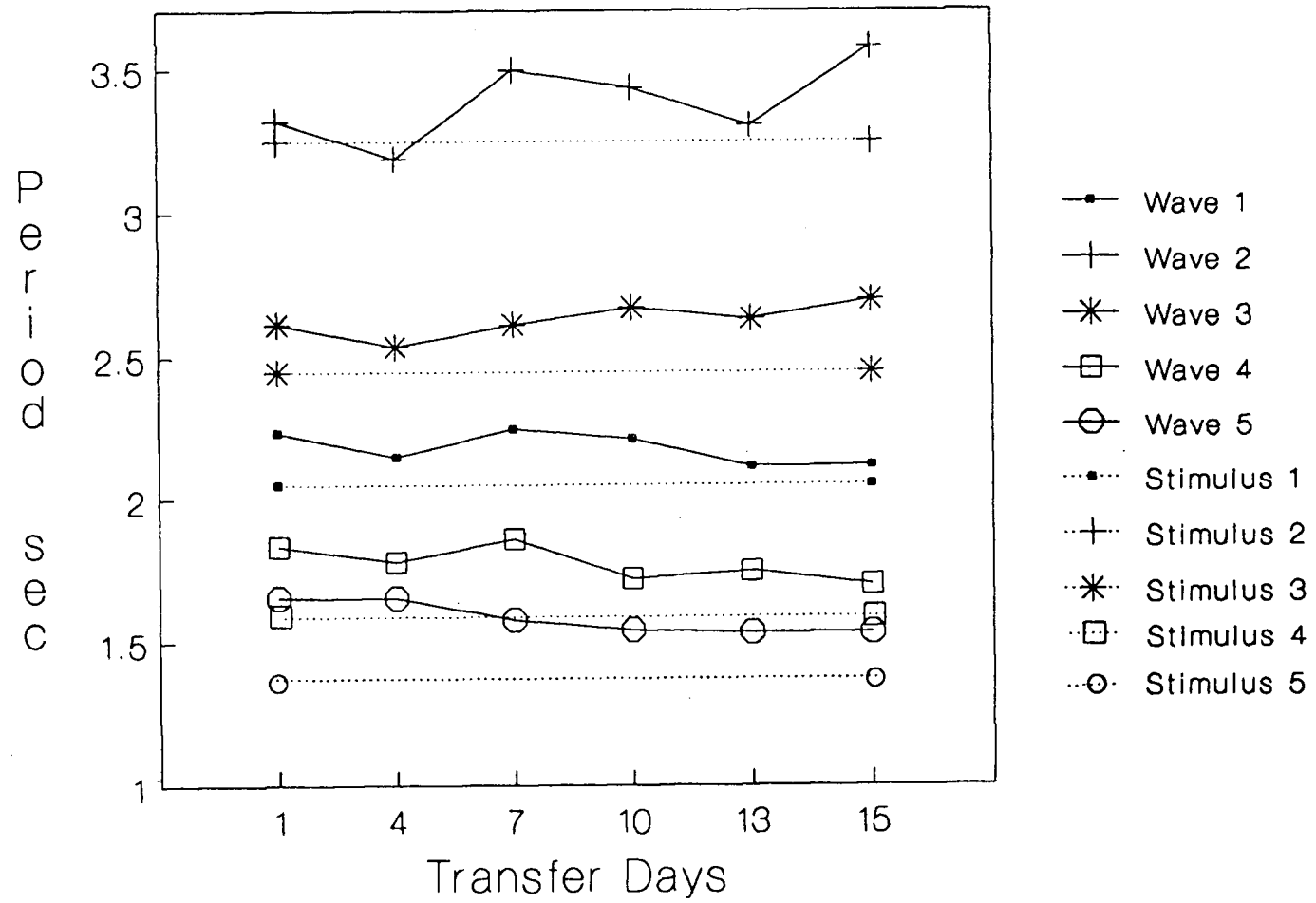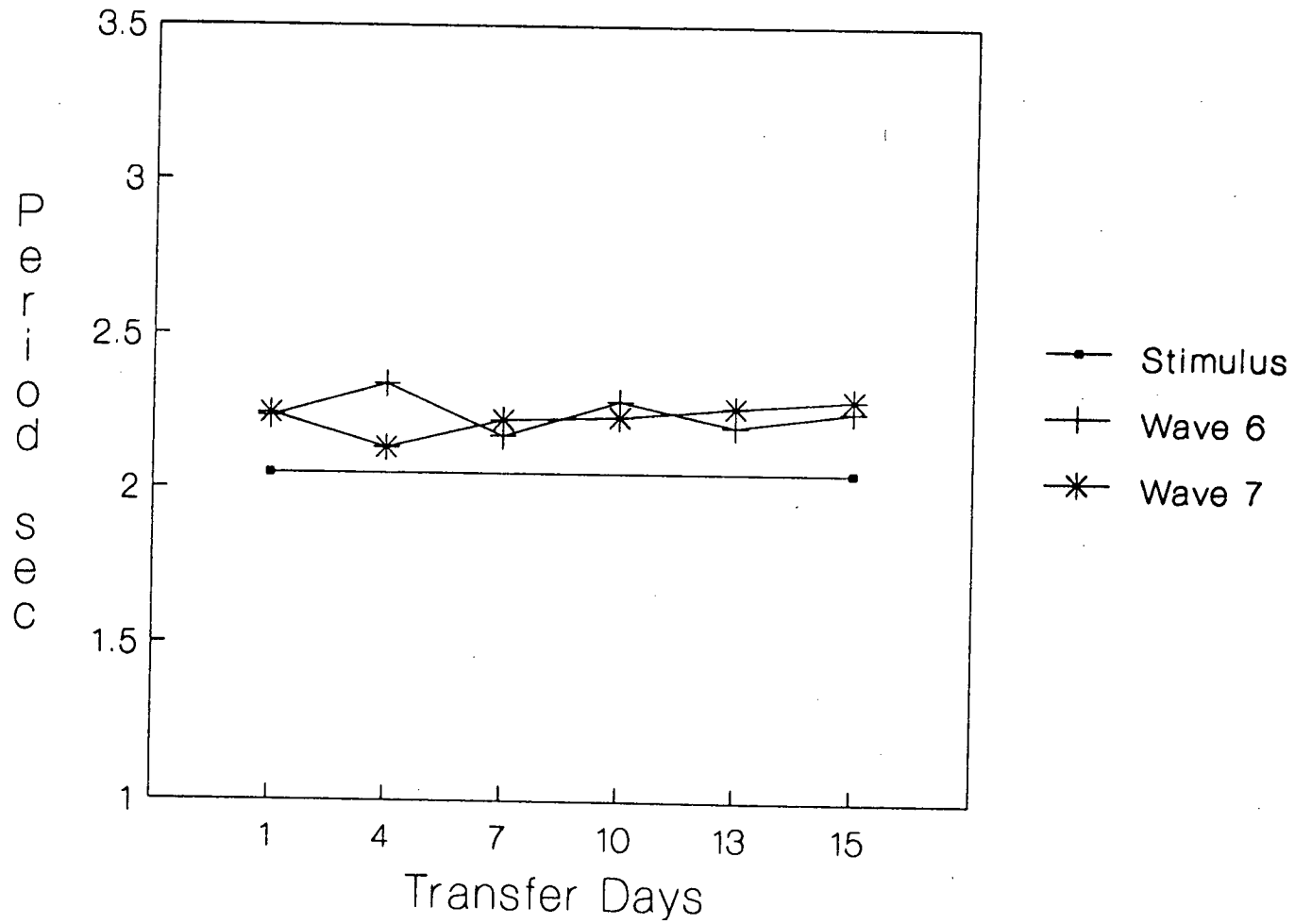
Period   Waves 1 - 5

Figure 11.

Mean period over five cycles of input blanking w6 & w7.

Period   Waves 6 & 7

reproduced responses on all waveforms (w1 - w7) that were consistently slow.

IV) RMS Error

In order to obtain a quantitative comparison of performance on the various waveforms in input blanking for day fifteen, an RMS error score was calculated for each of the five cycles from input blanking. The stimulus was shifted backward and forward in time in order to find the lowest RMS error score between stimulus and response for a given cycle. Of the RMS values calculated for each of the five cycles, the cycle with the lowest RMS value is presented in Table 8. (For kinematic representations of these responses plotted against the stimulus for the training waveform (w1) on day 15, see Appendix C. See also Appendix D for individual subject plots of the variability of the input blanking responses from the training waveform (w1) on day 15.)

Table 8 - RMS Error   Input Blanking Day 15
(units in 1/10 mm)

	w1	w2	w3	w4	w5	w6	w7
s1	68	41	31	91	74	56	41
s2	40	26	29	20	32	57	86
s3	84	85	91	106	103	108	109
s4	45	40	75	40	38	51	74
s5	33	57	53	39	48	75	88
s6	52	31	42	62	63	70	113
Mean	54	47	53	60	60	69	85

There were no statistically significant differences among the RMS error scores that were derived from the input

blanking data. However the descriptive data indicate that the subjects performed better on the training and varied speed waveforms (w1 - w5) than they did on the phase shifted waveform (w6). In addition, subjects seemed to perform better on the phase shifted waveform (w6) than on the entirely new waveform (w7). These RMS error scores were subjected to a repeated measures ANOVA using the orthogonal contrasts as presented in Table 9 below.

Table 9   **ANOVA Table** RMS Input Blanking
                       Orthogonal Contrasts   **Day 15**

CONTRAST	F	DF	P
1) W1 vs W2-W5	0.06	1, 5	0.809
2) W2 & W3 vs W4 & W5	0.91	1, 5	0.385
3) W2 vs W3	1.14	1, 5	0.334
4) W4 vs W5	0.01	1, 5	0.999
5) W1-W5 vs W6 & W7	6.85	1, 5	0.047
6) W6 vs W7	3.44	1, 5	0.123

V Frequency Composition

Input blanking data from day 15 were subjected to an harmonic analysis in order to determine the frequency composition of the response waveforms of w1 - w7. This analysis gave a more detailed description of the waveforms than could be derived from the RMS Error results. Figures 1 - 7 (Appendix E) represent the mean values of the harmonic components contained in the responses of the six subjects plotted beside criterion stimulus values.

Though there is no simple way to make quantitative comparisons amongst the frequency profiles derived from the

various waveforms through harmonic analysis, these frequency
profiles can help in determining what underlies the
differences found in the RMS error results. In comparing w6
(the phase shifted waveform) and w7 (the new waveform) it
seems that w6 and w7 (whose stimuli both contained three
component frequencies) are of similar accuracy with the
exception of the fourth harmonic. The amplitude of the
fourth harmonic of w7 is 3.6 mm larger than that of the
stimulus, whereas the amplitude of the fourth harmonic of w6
is only 1.1 mm larger than the stimulus. The larger
amplitude of the fourth harmonic may have contributed to the
larger RMS Error value in w7 as compared with w6.
Additionally, w7 also had higher amplitude values for most
of its residual component frequencies (i.e. comparing 2 to
3, 5 to 5, and 6 to 6) than did w6. Waveforms which contain
higher amplitude values on the residual component
frequencies will be less accurate reproductions of the
stimulus than those which have lower amplitude values on the
residual component frequencies. This may also have
contributed to the higher RMS error value on w7 as compared
with w6.

VI) Kinematic Profiles

Figures 12 & 13 contain the plots of two individual
subjects across the five waveforms. These plots give a
kinematic representation of the movement being made in the

input blanking situation. After fifteen days of extensive practice on the training waveform (w1), these subject were extremely consistent in producing this particular waveform. There was also a great deal of similarity in response production not only within a particular trial, but also between trials that required responses of different speeds. One other interesting point to note about a subjects consistency of response, is that all subjects produced a required response that approximated the stimulus (this approximation was more accurate as learning progressed) but subjects produced their own particular brand of error, or caricature of the movement. And this caricature was reliable both within and across waveforms of different base frequencies. Take for example the first topological element in the response waveform of subject 6. This subject consistently fabricated a reversal in the response, that did not exist in the stimulus. In comparing these instances with the other subjects, it seems that each subject developed his or her own unique caricature of the movement. Each subject seems to have made certain systematic distortions in the stimulus waveform in attempting to reproduce it.
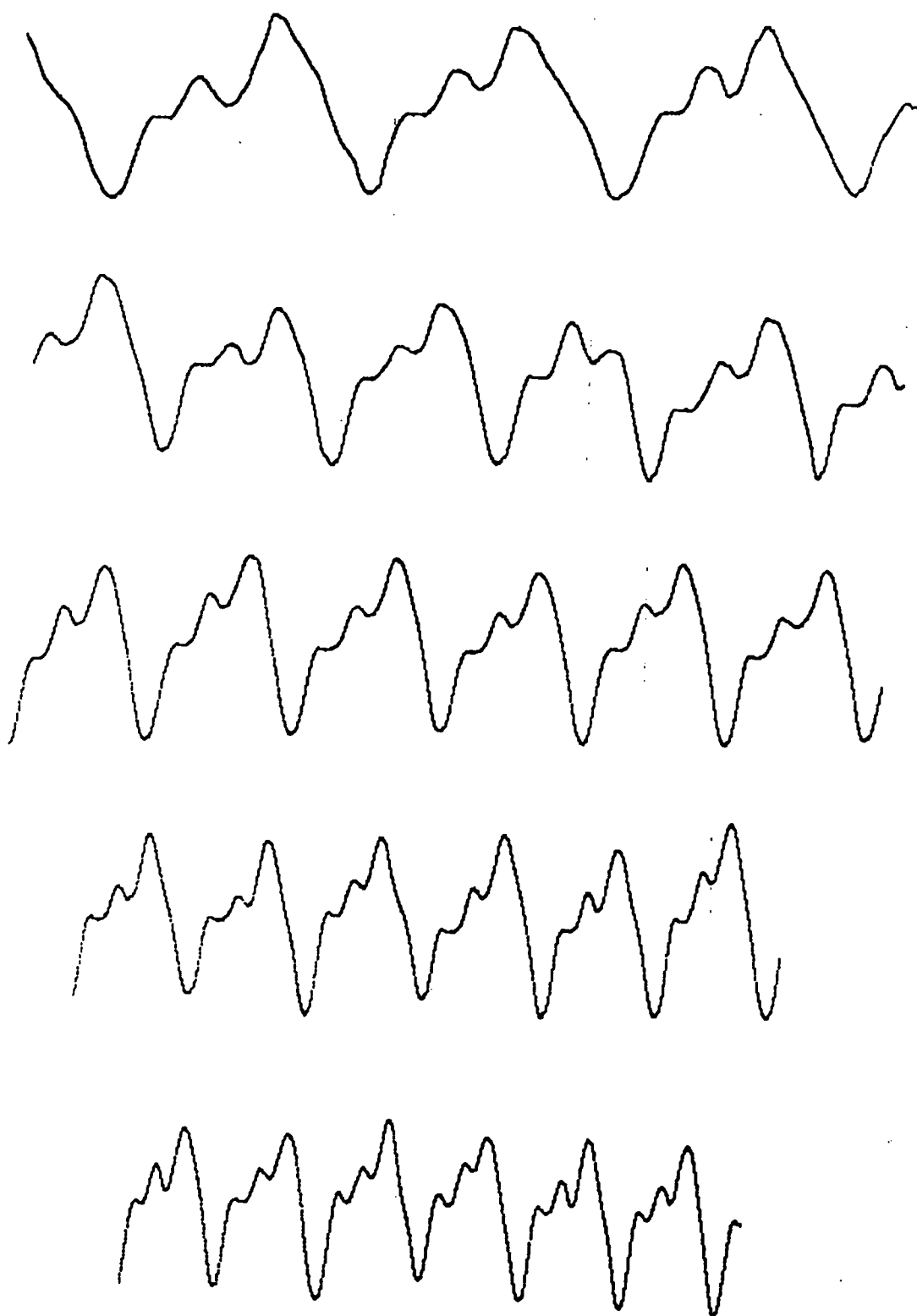
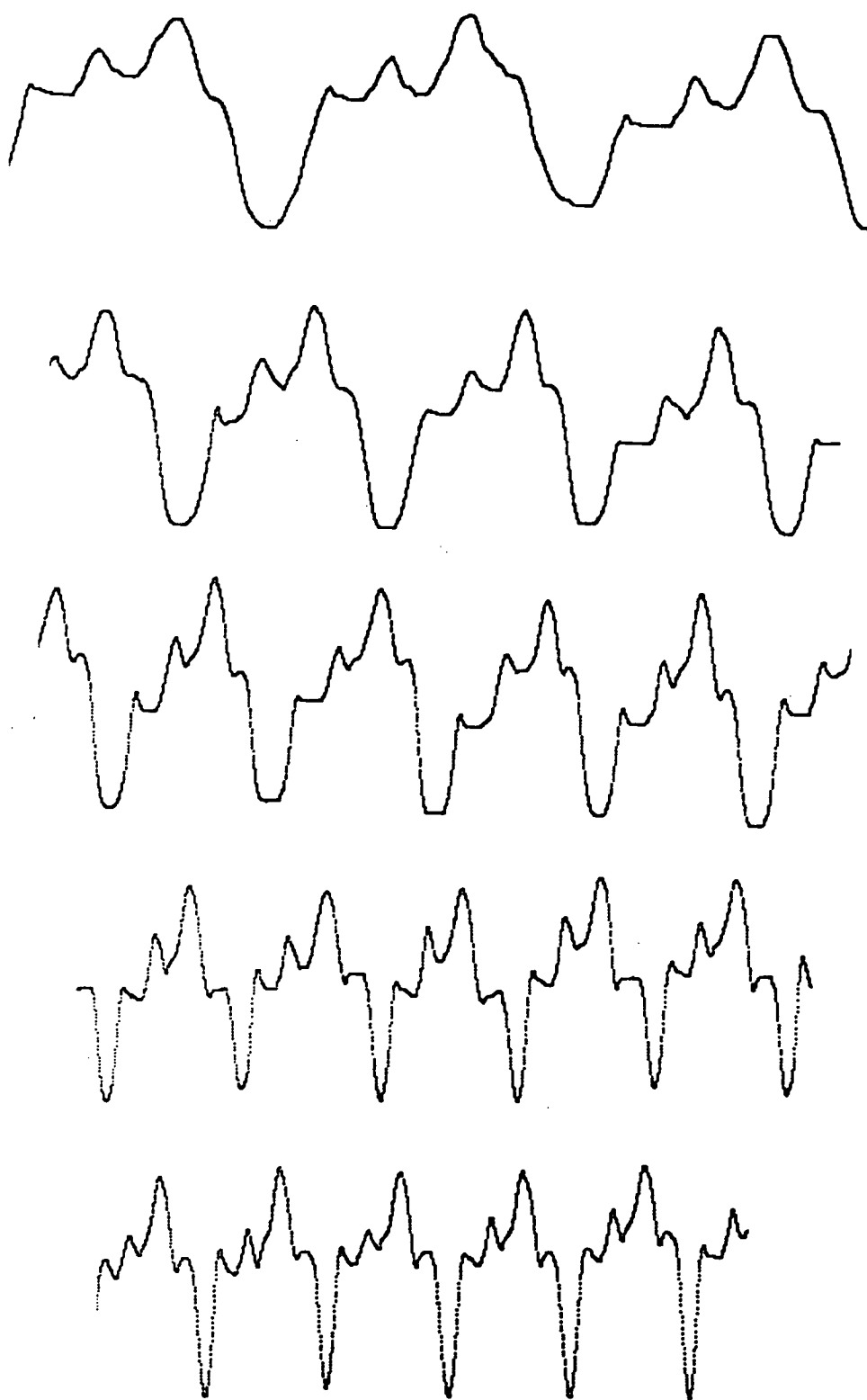Figure 12.   Kinematic profiles from subject 2 (w1 - w5).

Figure 13.   Kinematic profiles from subject 6 (w1 - w5).

CHAPTER 4.

DISCUSSION

The underlying purpose of this thesis was to investigate the question **what is learned**. Two possible answers to this question were the focus of this study. The first of these was that humans learn a movement in terms of the **relative timing** of the response elements that make up that movement. The second of these was that humans learn a movement in terms of the **frequency composition** of that movement. The results generated from this study speak not only to these specific aspects of the question **what is learned** but to other facets as well.

PART ONE - PURSUIT TRACKING

Two specific questions, with respect to **what is learned**, were put forward in relation to the subjects' performance in the pursuit tracking phase of this study. These were: One, would subjects perform equally well while tracking stimulus waveforms which maintained the relative timing of the training waveform, but were transformed in terms of their base frequency? Two, would subjects perform better while tracking a stimulus waveform which contained the same component frequencies as the training waveform (but different phase angles) than they would on an entirely new stimulus waveform?

Subjects performance over the fifteen days of the study on waveforms one to five (the training waveforms and the varied speed waveforms) exhibited a similar pattern of improvement on each of the three dependent measures (RMS error, variability, and response lag). Performance, as measured by RMS error and variability showed a quadratic decrease typical of most learning studies (Franks, Wilberg, & Fishburne, 1982; Marteniuk & Romanow, 1983).

By the last day of the study, day 15, subjects were performing more accurately (as measured by RMS error scores) while tracking the waveforms that varied only in base frequency or speed (w1 - w5) than while tracking the waveforms that varied the phase relationships among the component frequencies (w6) or varied the component frequencies themselves (w7). The fact that subjects performed better on the two faster speeds (w4 & w5) than they did on the other two periodic waveforms (w6 & w7) is especially interesting because typically it is more difficult, as evident from RMS error scores, for a subject to track faster waveforms (Noble, Fitts, & Warren, 1955; Pew, Duffendack, & Fensch, 1967). Despite this fact subjects were able to more accurately track these two faster waveforms (w4 and w5) than they were able to track the new and phase shifted waveforms (w7 and w6). These data, therefore, lend support to the hypothesis that subjects learn a movement in terms of its relative timing rather than in terms of its absolute timing.

The hypothesis that movement is learned in terms of its frequency composition was not supported by the RMS error results for the pursuit tracking phase of this experiment. If subjects learn a movement in terms of its component frequencies, they would be expected to perform better on a waveform which contained the same component frequencies as the training waveform (such as w6) than they would on an entirely new waveform (such as w7). However this was not the case; subjects performed no better on w6 than they did on w7.

In examining performance on the random waveform (w8) over the period of acquisition, it is evident that subjects improved slightly. Improvement on this waveform was indicative of a subject's ability to track without the periodicity that existed in the other waveforms, and was reflective of learning the control functions of the task. The control functions of the task could be summed up as the following: 1) learning the relationship between the movement produced with the joystick and the consequent movement of the response cursor on the screen 2) learning the maximum amplitude range of the stimulus cursor.

As is evident from Figure 1, waveforms 1 to 5 displayed a greater rate of tracking improvement than w6 and w7. The days effect on all of the varied speed waveforms (w2 - w5) contained a quadratic component similar to that of the training waveform (w1). W6 and w7 had no such quadratic component and exhibited only a linear decrease in RMS Error.

Thus there was transfer of learning between the training waveform (w1) and the varied speed waveforms (w2 - w5). What characteristics do the training waveform and the varied speed waveforms have in common? The varied speed and training waveforms were identical in terms of their relative timing and in terms of their spatial characteristics. These waveforms were two dimensional waveforms, the two dimensions being temporal duration and spatial displacement. The relative timing and the relative displacement defined the topology of these waveforms, and would be what Gel'fand and Tsetlin (1962, 1971, cited in Kugler et al., 1980) have called essential variables. These waveforms were different in terms of their overall timing or base frequency, which is what Gel'fand and Tsetlin would call a non-essential or scalar variable. Non-essential variables do not influence topology. The fact that subjects showed a similar trend of improvement on these waveforms would indicate that they learn a movement in terms of its topology rather than in terms of its scalar characteristics such as overall timing.

The pattern of improvement found in the RMS results, is also found in the variability results, indicating that as subjects become more accurate, they also become less variable in their responses. The increase in consistency that occured during the acquisition of this tracking task has been found in many studies on learning and skill acquisition (Burgett, 1970; Franks & Wilberg, 1984; Glencross,1979; Lewis, 1956; Marteniuk & Romanow, 1983).

The processes underlying such a decrease have been the subject of speculation. It may be that early in learning, subjects were using a variety of different strategies in attempting to track the stimulus, whereas later in learning they seem to have adopted a more consistent tracking strategy. In investigating typing, Lundervold (1958) found that during the process of skill acquistion typists developed a more efficient pattern of muscular contraction as measured by EMG. Fewer motor units were recruited to execute the typing task. Glencross (1979) found a similar change in EMG over the course of learning, and found also that this change in EMG coincided with a decrease in kinematic variability.

Figures 3 and 4 depict how subjects adjusted the time of responding with respect to leading or lagging the stimulus. The response to all waveforms early on in learning was temporally retarded, but as learning on w1 progressed, responses to all waveforms moved toward a coincident response. By day 15, the subjects' responses to w1, w2 and w3 were temporally aligned with the stimulus. On w4 and w5 the subjects' responses slightly lagged the stimulus by 7 & 5 ms respectively. On waveforms w4 and w5 the subjects may have been providing a response that was accurate in terms of its relative timing characteristics, but because of the speed of the stimulus, they were not able to keep up with the stimulus. In addition response errors become exaggerrated at the faster speeds because the

stimulus speed makes it more difficult for subjects to bring the response cursor back in alignment with the moving stimulus.

PART TWO - INPUT BLANKING

Two specific hypotheses, with respect to *what is learned*, were put forward in relation to the subjects' performance in the input blanking phase of this study. These were: One, subjects would reproduce w2 - w5 (the various speed waveforms) as well as they reproduced w1 (the training waveform). Two, subjects would reproduce a waveform which contained the same component frequencies as the training waveform phase shifted (w6) better than they would reproduce an entirely new waveform (w7).

I. *Interval Durations*

As described in the results, the ANOVA performed on the proportional interval durations yielded a non-significant effect for the waves by intervals interaction. Thus the proportional interval durations appear to be invariant, and the invariant relative timing hypothesis supported. It is interesting, therefore, to consider this result in light of findings and contentions from several recent papers, and in light of other data from the present experiment.

Gentner (1987) has criticized the procedure (followed in the present study) of taking means across subjects and across instances within a given subject. However, if the

within subject variability scores are examined in conjunction with the ANOVA, this provides an adequate test of consistency (or invariance). From the coefficient of variation tables in the results, it is evident that compared to other motor behaviors (such as reaction time) the within subject variability of the proportional interval duration data is low. To date, it has not been determined how consistent scores must be in order to be considered invariant. In comparison to other motor behaviors such as reaction time the proportional interval durations from the present study exhibit very low variability.

A recent study conducted by Heuer and Schmidt (1988) seemed to give evidence against the transfer of invariant relative timing between movement patterns. However, in Heuer and Schmidt's study subjects were given little practice (250 cycles). This amount of practice may have been insufficient to allow subjects to learn the relative timing of the training pattern. In examining the power spectra of the subjects' responses it is clear that subjects were unable to reproduce even the relative timing of the pattern they had trained on with any degree of accuracy. Thus it is not surprising that there was no difference in transfer between patterns which shared the relative timing of the training pattern and those which did not.

Perhaps if subjects in the Heuer and Schmidt study had been given more practice, there would have been a better transfer to the pattern which shared the relative timing of

the training pattern. By the last day of the present study, day 15, subjects had had 5740 cycles of practice on the training waveform, and had thus been given more time to learn the relative timing pattern of the training waveform. This may explain the apparent discrepancy in the results of the two studies.

Two hypotheses in reference to relative timing have been put forward by Heuer (1988). The first is that "different temporal patterns are **categorically** different", and controlled by different motor programs. The second is that "temporal patterns differ on one or more **continua**" such that movements falling at different places along these continua are controlled by different parameters within the same motor program. The categorical\continual hypotheses were not relevant to the present study because, the present study did not address the question of whether relative timing is an invariant feature of a **motor program**, but whether subjects **learn** invariant relative timing. In the context of the present experiment, relative timing is seen as an invariant that is learned or abstracted out of movement, rather than as a fixed structure of a motor program. Thus the theoretical context out of which the present experiment was developed is different than that surrounding the motor program.

Heuer and Schmidt (1988) in discussing relative timing have made the distinction between processes that are mandatory and those that are strategic. They suggest that

relative timing is strategic and not mandatory. From the perspective of the current study, invariant relative timing is not mandatory in the sense that it is impossible to change it, but then again most learned behaviors are malleable. Living nervous systems (especially the human nervous system) are plastic and by their nature designed to adapt to change. From the perspective of learning, invariant relative timing is seen as an aspect of movement that is **learned** by the subject and by that fact also capable of being changed (i.e. malleable).

The interval duration data can be considered in light of some of the informal observations and self report data from both pilot and thesis experiments. This data supports the notion that people may learn movement in terms of its rhythmic pattern, the rhythmic pattern being essentially an abstraction of the relative timing pattern of the movement. Over the course of skill acquisition, subjects learned to express the rhythm of the movement pattern that they were training on, in other sensory modalities and with other body parts. Subjects seemed to encode the rhythm of the movement pattern in the auditory modality. Many subjects reported that they would hum or tap the rhythm of the stimulus to themselves. In addition some of the subjects would move their head in the pattern of the stimulus both while tracking and while input blanking. Therefore it may be that one aspect of learning movement is learning its rhythmic pattern, and encoding this pattern in various modalities.

This expression of rhythm is found not only in movement and audition, but also in the development of anatomical structure. Bateson (1982) has observed the occurrence of rhythm during the process of morphogenesis:

The anatomy of the crab is repetitive and rhythmical.

It is, like music, repetitive with modulation. Indeed,

the direction from head toward tail corresponds to a

sequence in time.

Living systems then seem to display rhythm not only in movement but also in structure. Rhythm may be a property shared by all living systems and manifesting in various ways. For instance rhythm is found in the cardiac and respiratory patterns of all animals as well as in their circadian rhythms of rest and activity. Common to all human cultures is the expression of rhythm in poetry, music and dance.

The expression of rhythm manifesting in more than one modality that was described above, can be explained by what Schmidt (1988) and others have called abstraction. Raibert (1977) and Merton (1973) have presented findings, similar to those of the present study, for handwriting. When handwriting was transferred to the non-dominant hand, to the arm (by immobilizing the wrist), to the mouth, and to the foot, the writing in all situations exhibited a consistent topological form, though it was variable in its scalar characteristics. From this it was suggested that subjects might have encoded an abstract representation of the

movement that they produced. An abstract code of movement would allow for the various manifestations of the movement in the various modalities.

Another way of interpreting this evidence is that a movement that is well learned becomes redundantly encoded in the nervous system, and that part of this redundant encoding might involve an encoding in other modalities. Pribram (1971) and Lashley (1950) have given evidence for such a distributed system for memory. Pribram, using the analogy of the hologram, has suggested that as a movement becomes well learned, the brain encodes the movement at a finer resolution in the same way that a complete holographic plate stores a finer resolution image than a piece of that plate is capable of storing.

Bateson (1982) has suggested that one of the properties that living systems exhibit is an invariance in underlying formal relations. As Bateson has pointed out in describing vertebrate morphology, though there may be an "asymmetry in size", one nevertheless finds "a deeper symmetry in formal relations". In the same way that symmetry of form organizes morphogenesis, relative timing may be the structure around which a movement pattern is organized. Several authors have drawn parallels between morphogenesis and motor learning (Berkinblit, Feldman, & Fukson, 1986 p.599; Turvey, 1986 p.624). Living creatures exhibit symmetry in terms of form, but rarely is this expressed in terms of perfectly equivalent magnitudes on the right and left sides of the

body. For instance, the right leg may be slightly longer than the left (i.e. the magnitudes are not exactly equivalent) but the form is symmetrical in that there are two legs, two knees, two feet and the form of these on the right is the exact mirror image of that on the left. The concept of relative timing can be considered in a similar light, and the process of abstraction can be considered as a process of determining the underlying formal relations.

II. *Interval Displacements*

The proportional interval displacements (intervals taken as a proportion of the maximum displacement that occurred in that cycle) were invariant across cycles and waveforms within a given subject. Thus it seems that both the **relative** spatial and the **relative** temporal characteristics of the response waveforms remained invariant across cycles and waveforms within a given subject. It was these two characteristics that defined the topology of the particular tracking waveforms that were used in this experiment. Therefore the topology of the response waveforms for a given subject remained invariant, while the scalar characteristics of those response waveforms varied to some extent. The scalar characteristic of overall duration varied greatly across waveforms. Subjects were able to vary this scalar characteristic while maintaining the relative timing and the overall topology. This gives support to the idea that one of the aspects of a movement that subjects

learn is the topological properties of a movement. Bernstein (1967) has suggested that we encode movement in terms of its topological properties. Pribram (1971) has modified Bernstein's idea suggesting that we encode movement in terms of anticipated force patterns. However, more recent studies by Soechting & Lacquanti (1981) give evidence that humans plan and control the kinematics of the movement trajectory rather than the forces used to produce the movement trajectory. Perhaps this discrepancy exists because both contentions are correct depending on which level of analysis one is addressing. Whiting and Den Brinker (1982) in integrating these two positions suggests just this, that both contentions are correct, in that force is what we are required to produce, but that at a higher level in the system we encode topology. Present data supports Whiting's contention.

III. Cycle Duration

From the results of this experiment it seems that subjects organized their movement patterns in terms of relative timing rather than in terms of overall duration. Subjects were more accurate at reproducing the relative timing pattern of the stimulus waveforms than they were at reproducing the overall duration of the stimulus waveforms. These results can be considered in light of an idea put forward by Kugler et al. (1980) that the nervous system encodes information in a way that is system scaled and

dimensionless. Overall duration implies some kind of external objective time clock, whereas if Kugler et al are correct, the nervous system would only "understand" time in a relativistic sense. In order for the organism to tune its response timing characteristics to conincide with events in the environment, the organism would utilize feedback from the environment. Then it would not be the overall duration, but rather the immediate timing characteristics in the environment, that would be of relevance to the organism in moving. In relation to timing, Pribram (1971) has suggested that rather than encoding absolute time in the brain, humans encode patterns of frequency information. Movement itself, according to Pribram, is encoded in terms of a Fourier transform, which describes movement in terms of its pattern of frequency composition. Fourier transforms for movement patterns which have different overall timing, but have the same relative timing are identical. Thus if movement is encoded in this way, only its relative timing characteristics would be important.

IV. *Frequency Composition & Root Mean Squared Error*

The movement patterns reproduced during input blanking for w6 (the phase shifted waveform) were more accurate as measured by RMS error than those generated for w7 (the entirely new waveform), though this difference was not statistically significant. It seems that in input blanking, subjects may transfer to w6 (a waveform which contains

identical component frequencies to the training waveform) more easily than they transfer to w7 (a new waveform). This data lends some support to the conjecture that has been put forward by Pribram (1971), Franks and Wilberg (1982), and Marteniuk and Romanow (1983) that subjects may organize memory for movement in terms of the component frequencies of that movement.

In pursuit tracking, subjects performed equally well on w6 and w7, and performed worse on these than they did on w1 - W5. Subjects may have performed differently in pursuit tracking than in input blanking on w6 and w7, because being driven visually during pursuit tracking, subjects may have been more attuned to the topology of the stimulus, whereas during input blanking when subjects were not driven visually they may have been attuned to the frequency composition of the stimulus pattern. In addition, during pursuit tracking subjects were less dependent on their memory of the movement because the stimulus was presented before them. In input blanking, however, with no stimulus available, subjects were required to rely on their memory for the movement. In this case, they fell back on what they had learned from w1. Because w1 and w6 contained identical component frequencies, subjects were able to generate a better reproduction of w6 than they were of w7 (an entirely new waveform). If memory is organized in terms of component frequencies, this would make it easier for subjects to reproduce w6 than it would for them to reproduce w7.

V.   Kinematic Profiles

The kinematic representations of the responses
generated during input blanking on w1 - w5, day 15, give
evidence for topological consistency within subjects. All
subjects were consistent in producing the five cycles within
a given waveform. There was also a great deal of similarity
in response production across the varied speed waveforms.
Additionally, though subjects produced a required response
that approximated the stimulus, they also produced their own
particular brand of error, or what Gibson (1969) has
labelled a "caricature" of the movement. This caricature
was reliable both within and across waveforms of different
base frequencies. For example the first topological element
generated by subject six is a reversal that did not exist in
the stimulus. Subject six generated this element for each
cycle on each of the five waveforms. Gibson (1969) found
similar distortions in her subjects' drawings of objects
that they were required to remember:

> ...(they) were in fact exaggerations of those features
> which made one plane distinguishable from others, so
> that the composites are in a sense caricatures. It
> seems, therefore, that memory images or schematic
> representations of the aircraft were indeed based on
> distinctive features detected while looking for
> differences.   (_Gibson 1969, pp.146-147_)

In comparing topology across the six subjects, it seems that
each subject developed his or her own unique caricature of

the movement. Each subject seems to have made some systematic distortions in the stimulus waveform in attempting to reproduce it.

An interesting comparison can be made between these findings and findings reported by Bartlett (1932). He found that subjects, in recalling stories, would distort the details to fit their own cultural context. More recently Tversky (1981) in her research on memory for spatial locations, has found that in recalling geographical locations subjects made systematic distortions of space. It appears that subjects systematically distort physical reality in favour of a psychological reality that is influenced or biased by previous experience. In the case of this particular experiment the distortions in the topology of the waveforms were different for each subject and consistent within a given subject..

PART THREE - CONCLUSIONS

Component Frequencies

The idea that subjects learn and organize a movement in terms of its component frequencies was not supported by the pursuit tracking results, but was partially indicated by the input blanking results. During pursuit tracking subjects exhibited equivalent levels of accuracy on the new and the out of phase waveform, and thus seem not to organize a movement in terms of its component frequencies during pursuit tracking. However during input blanking, subjects

seem to have performed better on w6 than they did on w7. The previous studies (Franks & Wilberg, 1980; Marteniuk & Romanow, 1983) that gave evidence that subjects learn movement in terms of component frequencies measured subjects during input blanking rather than pursuit tracking. Thus evidence from the present study is consistent with evidence from these earlier studies.

Relative Timing

The hypothesis that subjects learn a movement in terms of relative timing was supported by this experiment in both the pursuit tracking and input blanking conditions. With practice in tracking the training waveform (w1), there was positive transfer to the various speed waveforms (w2, w3, w4, w5). For pursuit tracking, if the transfer waveform was slower (w2 or w3) than the training waveform (w1), there was almost perfect transfer in terms of response accuracy. When transferred to faster waveforms (w4 and w5), the response accuracy was somewhat diminished. Nevertheless, subjects performed far more accurately on the faster transfer waveforms (w4 and w5) than they did on the new waveform (w7) and the phase shifted waveform (w6). For input blanking, the interval durations that were calculated revealed that the proportional interval durations were invariant across the five varied speed waveforms, thus supporting the notion that skilled movement is characterized by invariant relative timing.

Typically in the field of motor learning and control
invariant relative timing has been thought of as an
invariant feature of a motor program. If subjects in the
present study had achieved identical RMS error scores for w1
- w5, the contention that relative timing is fixed in the
motor program, and that overall duration is a parameter
whose value can vary might have been supported. However the
data from this experiment did not turn out exactly as
predicted. One reason for this is that faster waveforms are
more difficult to track, and thus as present results show,
one finds higher RMS scores on these waveforms.
Additionally, in the case of pursuit tracking, subjects used
feedback to continuously modulate their response, making the
notion of a discreet parameter value unlikely. For pursuit
tracking it is likely that the overall (or absolute) timing
is continuously modulated by feedback.

From both the input blanking and the pursuit tracking
data, there is evidence that relative timing is one of the
aspects of a movement that people learn during the process
of skill acquisition. The evidence that a pattern of
invariant relative timing was learned during the process of
skill acquisition need not be taken to mean that invariant
relative timing is an invariant feature of a generalized
motor program. It can just as well be taken as support for
the idea that relative timing is one of the invariances that
is learned during motor skill acquisition, perhaps in a

similar way to the pick up of invariants during perceptual
learning (Gibson, 1966; Gibson, 1969).

What is Learned?

Both thesis and pilot experiments lend support to the
idea that **relative** timing (of the response elements that
make up a movment) is one of the aspects of movement that is
learned. This finding is limited to cyclic movements of
two kinds: those in which visual feedback is involved in the
control of the movement such as in pursuit tracking, and
those in which both kinesthetic feedback and memory are
involved in the control of movement such as in input
blanking. These results also give some indication that
during response reproduction a movement may be organized in
terms of its component frequencies. This finding is limited
to tasks such as input blanking in which the control of
movement is based on kinesthetic feedback and memory. Both
the relative timing and the component frequencies of a
movement can be seen to be a way of organizing movement,
such that as learning progresses the person moves toward a
higher state of organization, in the same way that as
morphogenesis progresses the system reaches a more complex
form of organization. Though learning is itself a process
that occurs in living systems, it has often been considered
as a "higher" function that is somehow removed from the rest
of the biological world, and therefore not governed by the
same laws. In contrast, the view of learning put forward in

this thesis has been that learning is a process rooted in biology, rather than one removed from it. Learning can be considered as an expression of life and governed by the same laws. In this thesis parallels have been drawn between principles of learning and principles of life. The most emphasized parallel has been that of the evolution toward a higher state of organization. Both in learning and in morphogenesis the human or organism goes through a process whereby the entropy gradient is reversed and the organism continually achieves a higher and higher order organization. The development of the coordinative structure is an example of such a process. It can be thought of as a form of internal organization, which, becomes both more differentiated and more integrated throughout the learning process, in the same way that the nervous system during its morphogenesis becomes more differentiated and integrated (Schacher, 1985). Learning then, can be considered as a special instance of the larger process of life.

APPENDIX A

REVIEW OF LITERATURE

A simple but essential question for those who seek to understand learning is **what is learned.** Or from the movement scientist's perspective "What changes within a person bring about more skilled motor performance?" This question has been central to psychology since the inception of behaviorism in the 1930's (Gibson, 1969; Weimer, 1977; Whiting, 1980). The behaviorists have proposed, that it is associations between stimuli and responses that are learned. The cognitivists, on the other hand, have argued, that **what is learned** are representations of movement, objects, or events. There has been much speculation as to the nature of the representation for skilled movement; it has been described in different ways by different researchers, with labels such as schema (Schmidt, 1975) image of achievement (Pribram), and motor program (Keele, 1975).

The Gibsonians or the ecological group, who like the behaviorists, have rejected explanations based on representation, have explained learning in yet another way. J.J. Gibson (1966, p.279) has defined perceptual learning as "cases of perceiving or detecting an invariant". J.J. Gibson's idea have be extended to both the cognitive and motor domains. In relation to cognition, Eleanor Gibson (1969, p471) has argued that the learned perceptual ability "to detect regularity, order, and structure" provides the

basis for cognitive abilities such as learning mathematics
(see also Wertheimer, 1945). In the case of movement as
well, there are certain of its features that become
invariant as it becomes well learned.

"What is Learned?"

Several researchers (Bartlett, 1932; Head, 1920;
Gallistel, 1980; Schmidt, 1975) have proposed that during
learning we develop a schema as a representation of a given
skilled act. This schema is a set of rules used to define
and generate movement. Bartlett, one of the first to have
conceptualized the notion of a schema, has included in it,
adaptation to a changing environment through feedback:

In a world of constantly changing environment, literal
recall is extraordinarily unimportant. It is with
remembering as it is with the stroke in a skilled game.
We may fancy that we are repeating a series of movements
learned a long time before from a text-book or from a
teacher. But motion study shows that in fact we build
up the stroke afresh on the basis of the immediately
preceding balance of postures and the momentary needs of
the game. Every time we make it, it has its own
characteristics. (1932, p.204.)

The other important point that Bartlett has made is
that memory or reproduction of movement rarely involves rote
recapitulation. Because the environment is always changing,
any skilled action must be adapted to the immediate

environment. And of course this can only be accomplished through feedback.

Another version of the representation for skilled movement is the concept of the image of achievement (Pribram, 1971) which is based on both neurophysiological and behavioral evidence. Pribram has suggested that the image of achievement is encoded in the motor cortex as a Fourier transform of the learned anticipations of force required to execute an action, and that it employs feedforward, tuning, and interaction with the environment. Pribram has given physiological evidence for the image of achievement and for the notion that we encode the frequency components of movement. Franks & Wilberg (1982) have also given support to the notion that we learn and organize a movement in terms of its component frequencies. In their study, subjects learned to track a waveform which consisted of three component frequencies with a base frequency of 0.5 Hz. In addition, subjects reproduced this waveform in an input blanking situation in which both stimulus and response cursors were removed from the display. The response was measured through a Fourier analysis which determined the component frequencies, amplitudes and phase angles that made up the response waveform. It was found that early in learning subjects only reproduced the fundamental frequency. However, as learning progressed subjects added higher frequency components to their response suggesting that subjects may systematically organize the continuous

movements that they learn in terms of the component frequencies that make up the movement. Other studies have also given evidence that support this interpretation (Bernstein, 1967; Marteniuk & Romanow, 1983).

Yet another version of the representation for skilled movement is the motor program (Keele, 1975) or generalized motor program (Schmidt, 1988). According to Schmidt (1988), the motor program exists at a lower level in the system than the schema, and is involved in the execution of pre-planned movement sequences. Since its inception in the early 60's the motor program has undergone some modifications. Keele's (1968) definition perhaps best characterizes the early versions of the motor program concept. At that time Keele defined it as "... a set of muscle commands that are structured before a movement sequence begins, and that allows the entire sequence to be carried out uninfluenced by peripheral feedback." This is an open loop explanation of motor control in which feedback plays no role. Since that time the concept of the motor program has developed such that some forms of feedback are now accounted for. The motor program is presently thought to be an open loop mechanism, which though it is structured in advance of movement, can be modified with feedback at lower levels in the system (e.g. the reflex level (Schmidt, 1988)). Thus the motor program is a higher level open loop structure which has embedded within it lower level closed loop processes, which are capable of adapting to minor

perturbations, but are not capable of changing the entire action.

From an alternative perspective, the learning of movement can be explained in terms of the notion of a ***coordinative structure***. As Tuller, Turvey, & Fitch (1982, p.255) have explained: "One of the things you are trying to discover in learning (a movement) ... is a way of linking or constraining those muscles involved so they become just a single entity". Kugler, Kelso, & Turvey (1980, p.17) have formally defined the coordinative structure as "a group of muscles often spanning a number of joints that is constrained to act as a single functional unit". Thus the coordinative structure serves in explaining the control of action which involves a coordination of several body parts (i.e. multi-movement coordination).

The coordinative structure, like the motor program, has undergone its own conceptual evolution. The term was coined by Easton (1972). Turvey (1977), borrowing Easton's term, developed the notion of the coordinative structure based on Berstein's (1967) concept of muscle synergies. At that point, in 1977, Turvey still allowed for an executive as a controlling agent, though one that intervened minimally. By 1980, however, Kugler et al (1980) had begun to see "control" as an inherent process of the self-organizing system, and had therefore removed the need for any recourse to an "executive" or to representationalism.

From a compatible theoretical perspective to that out

of which the coordinative structure developed, are J.J.
Gibson's (1966) speculations on learning. In a discussion
on the nature of memory, he has considered the question of
what is learned:

> An observer learns with practice to isolate more subtle
> invariants during transformation and to establish more
> exactly the permanent features of an array.

> > (1966, p.265)

In perception, humans learn to detect invariants. In
movement learning (specifically tracking) subjects may learn
to detect the invariants of the stimulus that they are
following. An example of such an invariant is the relative
timing of response elements within a complex motor act. In
order to maintain the topology of such a movement, one must
maintain its relative timing. One can however, vary the
absolute timing, while still maintaining the topology.

Bernstein (1967, p177) in reference to topology, has
pointed out that "a function is well organized if its
arguments can be separated into: 1)essential variables and
2)non-essential variables". Essential variables are those
that preserve the topological properties of movement; these
would parallel Gibson's invariants. Non-essential variables
are scalar changes, for example the overall rate or speed of
a movement. Thus, in the learning of movement, **what is
learned** are the essential variables (or invariants) i.e.
those variables that are responsible for preserving the
topology of movement.

The essence of learning (and even life itself) may be pulling invariants (or order) out of apparent chaos. Schrodinger (1944) has argued that this is the essence of all living systems. Many of our explanations in motor control and learning have to do with the interplay of variance (entropy) and invariance (order). For example, schema theory (Schmidt, 1975) has explained learning in terms of finding invariance and developing an equation that expresses what is variable and what is not variable. From another perspective, the action theorists have postulated an equation of constraint, which also defines what is invariant and what is variable. From both perspectives, two simultaneous processes are occurring. 1) certain things in movement vary, and 2) certain things in movement are invariant. Learning is based on establishing an organization in which certain relationships become invariant, while others are left free to vary.

An alternative to the notion of representation, then, is organization. As such, learning would consist of a process of shifts in the internal state of organization toward a higher form of organization. There has been evidence to indicate that both processes of learning and processes of life involve organizational shifts toward a higher order organization. Schrodinger (1944) has differentiated the living from the non living in terms of order and entropy. He has suggested that "living organisms drink order out of their environment" and in so doing, defy

entropy. As living organisms evolve they progress to higher order levels of organization. Gentile & Nacson (1976) have also suggested that this is the basis of learning. Though in this paper, they did not consider the concept of organization, as an alternative to representation, the paper was nonetheless one of the first to apply the concept of organization to the field of motor skills. They contended that the organization that develops with practice is in the form of various "rules for encoding input" and that what is learned are "contextual relationships among positions" (Gentile & Nacson, 1976, p.16)

There is also evidence from tracking studies for such a process occurring in learning. Fuchs (1962) found that subjects moved to higher order control systems over the course of learning a tracking task such that with learning, subjects developed a higher level of perceptual motor organization. Fuchs had subjects track a complex waveform. In modelling their behavior mathematically, he found that early in learning, performance could be modelled in terms of displacement and velocity control. Further on in learning, the weighting shifted to the increased utilization of acceleration, and later delta acceleration information. In addition, when subjects were given the added stress of having to concurrently perform another task, they regressed to an earlier stage in which they were using lower derivative information. This progression during learning, and regression during stress, was termed the progression-

regression hypothesis. Recently, Jagacinski and Hah (1988) have replicated this finding.

The morphogenesis of the nervous system also provides us with numerous examples of the progression toward higher order forms of organization. Both processes of learning and processes of evolution, involve such a progression. And one can draw a parallel between these processes as Fowler & Turvey (1978, p.3) have done:

"Insofar as a species is said to be a particular biological attunement to a particular niche, we may wish to say , perhaps curiously, that the individual animal, as skilled performer, is a particular attunement to the particular task it performs skillfully."

Representationalism and the Problem of Higher Authority..

When learning is conceived of in terms of organization, it becomes unnecessary to invoke representation and higher authority in explaining the process of learning. The notions of representation and higher authority are related in that any explanation which invokes representation necessarily "implies an animal analogue which in turn implies an infinite regress" (Kugler et al., 1980). In other words when one speaks of representing movement, one implies a representation *to* some entity (such as the homunculus, executive, or soul). Representationalism is one of the central issues the motor action controversy (see Beek & Meijer, 1988; Meijer et al., 1988). In attempting to

understand learning, one comes face to face with this issue.
As the cognitive neuroscientists, Maturana and Varella, have
stated:

"Indeed, if the nervous system does not operate - and
cannot operate - with a representation of the
surrounding world, what brings about the extraordinary
functional effectiveness of man and animal and their
enormous capacity to learn and manipulate the world?"

(p.133, 1987)

They have proposed a solution to the problem of
representationalism. Though learning may not involve
representation of movement, it does involve changes in the
brain, which bring about more skillful movement. Instead of
conceiving of these changes as representations, they can be
thought of as states of internal organization, which
transform with learning such that the interactions between
the person/organism and the environment are different.
Maturana and Varella (1987) have suggested, that these
internal changes be thought of in terms of internal
correlations between sensory and motor processes. Consider
an experiment conducted by Sperry (1945) as an illustration
of this idea. A frog when presented with a fly in his
visual field, will stick his tongue out and catch the fly.
Sperry surgically rotated the eyes of a frog by 90 degrees.
After the surgery, when he presented the frog with a fly,
the frog stuck its tongue in a direction exactly 90 degrees
away from the actual location of the fly. Thus the frog's

nervous system seems to have correlated sensory and motor
events, rather than to have represented the external
environment in its brain. Skilled human movement would
encompass a highly complex and integrated array of such
correlations, facilitating a highly efficient interaction
with the environment.

The problem of representationalism versus solipsism has
been a perennial problem for those attempting to understand
cognition, and its roots extend as far back as the classical
period (Maturana & Varella, 1988). Currently, the field of
motor learning and control is dominated by a
representationalist's perspective, this having been
inherited from motor learning's parent discipline, cognitive
psychology. At this point in history then,
representationalism is favored over solipsism. At other
times in history, the reverse has been the case. Part of
the reason for cognitive science's tendency to embrace
representationalism, has been its association with the field
of artificial intelligence. There is however a certain
irony inherent in this particular borrowing of ideas.

Dreyfus (1985), following ideas developed by the French
philosopher Merleau Ponty, has argued that as humans, we
have no need to represent our bodies to ourselves, as a
computer would have to do, because we are embodied.
Dreyfus, then, is a monist who sees mind and body as a
unity. In these terms, his approach can be distinguished
from the traditional theorizing in motor control (and its

parent science, cognitive psychology) which is based on dualistic assumptions which not only separate mind and body, but conceive of mind as causally primary.

Cognitive psychology has attempted to explain cognition in isolation from the body, and from the sensory motor interactions with the environment. However, this has presented a problem in that human cognitive ability develops out of early sensori-motor interactions with the world (Piaget, 1963). Thus cognition cannot be isolated from the body. In borrowing from the present cognitivist paradigm, movement scientists have picked up the wrong end of the stick (Kuhn, 1962).

The idea that our cognitive abilities are intrinsically motoric is not entirely new, and has been proposed before by a small group of psychologists (Bartlett, 1958; Klapp, 1976; Weimer, 1977), neurophysiologists (Pribram, 1971; Young, 1975), and anthropologists (Sapir, 1921). The anthropologist Edward Sapir believed the appreciation of art to be a motoric function. Along similar lines, Bartlett (1958, p199) has proposed that thinking is an advanced form of skilled behavior in that "it has grown out of these earlier forms of flexible adaptation to the environment". From Pribram's (1971) neurophysiological evidence that the motor cortex is sensory in nature, it can be concluded that the mind is a generator not only of its own output but also its input" (Weimer, 1977).

Ironically, movement scientists have borrowed

information processing models from psychology which artificially separates perception and action, and then ignores and degrades action. Thus movement scientists have tended to ignore the fact of embodiment. Perhaps it has been easier to explain movement control in terms of a deus ex machina (Kelso et al., 1980) than in terms of processes within the embodied organism itself. Dualistic assumptions may well have led to explanations based upon a "god outside of the machine".

Tamboer (1988 p.445), in considering the question of dualism and embodiment, has written:

" If a tenable and comprehensive interpretation of the 'facts', discovered in the field of human movement behavior is sought, the images of the human body, which lie at the root of the various approaches by which that field is scientifically defined, cannot be neglected".

In having borrowed the scientific paradigm of cognitive psychology, movement scientists have been led away from embodiment. Because of this, they have often created explanations of motor control in which the "executive" is deemed to be the "controlling entity" which "commands" the lower levels. This problem seems not to be unique to psychology and movement science.

"The nature and power of higher / central / commanding / controlling entities, has been a problem for western science in general ever since the seventeenth century. The quest to avoid superior authority, then, appears to

have had - and still has - considerable ramifications."

<div style="text-align: right">(Meijer, 1988 p.171)</div>

This particular problem may have an even deeper origin than Meijer suggests. Fox (1983) and Merchant (1980) discuss the long-standing religious, philosophical and cultural roots of the problem of superior authority, and its relationship to the problem of embodiment. These companion problems have their roots in the cultural/religious context out of which modern western science has emerged.

Modern science in its inception was wed to religion. Prigogine and Stengers (1984, p.50) have pointed out the consequences of this marriage:

> Man is emphatically not part of the nature he
> objectively describes; he dominates it from the outside.
> Indeed for Galileo, the human soul, created in God's
> image, is capable of grasping the intelligible truths
> underlying the plan of creation ... that God himself
> possessed.

For the sciences of psychology and motor behavior this has presented an interesting dilemma. How can we who study human behavior, dissociate ourselves from that which we "objectively describe", when we are ourselves the objects of that description.

This problem has been dealt with by saving a part of the human as the soul, though science has rarely labelled it as such. Rather it has been given titles such as the homunculous or the executive. Interestingly it has been

this part of the human that has usually been seen to be the part that is "in control". Thus in the same way that Galileo believed man was able to both dominate and fully understand nature, so the executive has been seen to be able to both dominate and fully understand the "lower" levels of the motor system. The notion of representation, as it has generally been conceived, has inevitably led to the problem of 'higher authority' (Carello, Turvey, Kugler, & Shaw, 1984; Maturana & Varella; Meijer, 1988; Reed, 1988).

Invariant Relative Timing

For several years there has been evidence that the relative timing of the components of a given skilled movement remain invariant over changes in the overall duration of that movement. Motor theorists have inferred from this that relative timing may therefore be an invariant feature of the central representation (usually motor program) of the movement being learned (Shapiro & Schmidt, 1982; Shapiro, Zernicke, Gregor, & Diestel, 1981). From another perspective, action theorists, though they have rejected the notion of representation, nevertheless have argued that relative timing is one of the invariants of a movement that humans learn (Tuller & Kelso, 1984; Kelso, Putnam, & Goodman, 1983). Thus invariance brings together both motor and action perspectives.

At least two questions can be asked with reference to invariant relative timing. They are:

1) Is invariant relative timing a characteristic of well learned movement?

2) Is relative timing an invariant feature of a motor program?

In asking the second question one makes a leap of faith, in that one must assume the existence of the motor program. Most of the traditional research on invariant relative timing has addressed the second of these questions. The present experiment is designed to address the first of these questions. However the second question is important on theoretical grounds. In order to consider the ramifications of the second question, one might frame it from an alternate perspective. Thus a third question might go something like this:

3) Is relative timing one of the invariances in the movement array that humans learn.

Most of the researchers who have studied invariant relative timing have studied it in relation to the motor program. A central question for those who have studied the motor program has been "What are its invariant features?", and it has been suggested (Schmidt, 1988) that relative timing is one of those invariant features. The idea that relative timing is an invariant feature of the motor program has been referred to in the literature as the generalized motor program with a multiplicative rate parameter or the proportional duration model. The proportional duration model predicts that any skilled movement performed with

different overall durations will exhibit fixed relative durations. Original evidence for this came from some unpublished studies by Armstrong (1970, cited in Schmidt, 1988). He had his subjects repeatedly move a lever through a particular unidimensional spatial-temporal pattern. When subjects moved too quickly they nevertheless maintained invariant relative timing. It has been proposed that this occurred because relative timing is structured into the motor program, whereas the overall duration is a parameter whose value can vary across instances of the skill. Thus, for each instance of the skill a different parameter value for overall duration is assigned to the motor program. The proportional duration model of timing in skilled motor performance has been widely accepted up until now. (For empirical research supporting this model see: Carter & Shapiro, 1984; Shapiro, 1977; Summers, 1977; Terzuolo & Viviani, 1979).

Recently Gentner (1987) has re-evaluated the supporting evidence for the proportional duration model. From his review it seems that much of the observed performance does not perfectly fit the model. Gentner has argued that the majority of the data used as supporting evidence for the proportional duration model was analyzed imprecisely in that researchers analyzed mean durations of a given interval instead of the actual individual observed durations. To overcome this problem, Gentner has proposed a **constant proportion test**. Assume that Di is the duration of the i-th

component of a complex movement and T is the total duration.
Then the relative proportion of Di with respect to T should
remain constant over changes in T. This is an expression of
the proportional duration model in mathematical terms. For
a given interval Gentner has taken the ratio of Di/T and
plotted it against T. If the slope of the resulting
function was zero the proportional duration model was
supported.

After having reanalyzed the data from experiments that
found evidence for an invariant relative timing feature
within a motor program, Gentner has concluded that the
proportional duration model is not supported. Relative
durations are maintained to some extent but not precisely.
But as Heuer & Schmidt (1988) have pointed out:

These deviations might still be considered as acceptable

discrepancies between nature and human

conceptualizations of it, and one can argue that they

are of minor importance as compared with the conspicuous

tendency toward invariance. (p. 241)

Though humans may not exhibit relative timing with
perfect invariance, one can not rule out the notion that
they may learn invariant relative timing. One could posit
at least four reasons for a lack of perfect invariance on
the behavioral level. The first has been suggested by Heuer
(1987), who has argued that a lack of invariance in relative
timing on the behavioral level, does not necessarily
indicate a lack of invariance centrally. This is because

there are non-linearities in the nervous system which may
distort a central invariance in relative timing, such that
it would manifest peripherally (behaviorally) in the form of
variable relative timing.

The second is that humans may learn relative timing in
a formal way (Thompson, 1952). As Bateson (1982) has
pointed out in describing morphogenesis, though there may be
an "asymmetry in size", one nevertheless finds "a deeper
symmetry in formal relations". In the same way that
symmetry of form organizes morphogenesis, relative timing
may be the structure around which a movement pattern is
organized. Several authors have drawn parallels between
morphogenesis and motor learning (Berkinblit,. Feldman, &
Fukson, 1986 p.599; Turvey, 1986 p.624). Living creatures
exhibit symmetry in terms of form, but rarely is this
expressed in terms of perfectly equivalent magnitudes on the
right and left sides of the body. For instance, the right
leg may be slightly longer than the left (i.e. the
magnitudes are not exactly equivalent) but the form is
symmetrical in that there are two legs, two knees, two feet
and the form of these on the right is the exact mirror image
of that on the left. The concept of relative timing can be
considered in a similar light. Gentner (1987) has given
evidence that interval durations are not always
mathematically perfect proportions of overall movement time.
This is analogous to Bateson's notion of "asymmetry in
size". Gentner's (1987) review also illustrates that on

average the proportions are invariant; this could be thought of as analogous to Bateson's notion of the "deeper symmetry in formal relations".

The third reason that invariant timing may not exhibit perfect invariance, is that feedback may somehow be involved in modulating the expression of relative timing. Because the intervals aren't perfect proportions of overall movement time, it seems unlikely that the present model of a program with fixed relative timing and an overall duration parameter is correct. In such a model relative timing must be maintained precisely. The duration parameter, once put into the program, is not modifiable. If, however, feedback were being used throughout the duration of a movement to control its absolute timing, this might bring about slight variations in relative timing.

The fourth reason that invariant relative timing is not found is that few researchers have considered the necessity of practice in the development of relative timing. For instance, in a recent study by Heuer & Schmidt (1988), in which subjects were given only 250 cycles of practice, it was concluded that relative timing does not remain invariant in a transfer task. However it is questionable whether 250 cycles is adequate practice for the development of invariant relative timing, or for the development of a motor program. The development of the motor program is presumably based on extensive experience with the environment such that an appropriate form of organization might develop. But, since

neither learning, nor the development of the motor program, are addressed, the problem of adequate practice is often over-looked.

Scientists from both sides of the motor action controversy, have recognized the importance of flexibility in movement control, and both sides have attempted to solve the problem of flexibility by developing models of motor control in which there is an interplay between that which varies and that which remains invariant. It would be unfortunate to reject a phenomenon such as invariant relative timing simply because its data do not fit the current motor programming perspective. The data, though they may refute the idea that invariant relative timing is fixed in the motor program, certainly do not refute the idea that relative timing is one of the aspects of a movement that humans learn. These two possibilities must be differentiated otherwise we may fall prey to neglecting an important phenomenon simply because we are wearing the wrong theoretical spectacles.

The proportional duration model, as a part of the theory of the generalized motor program, is a theory of motor control that emphasizes open-loop processes, though it allows for feedback at lower levels in the system. One need not accept the existence of the generalized motor program in order to accept that relative timing is an invariant characteristic of skilled action.

Two criticisms can be made of the generalized motor

program theory as it stands to date. Both point out the

necessity of accounting for feedback, which the theory has

failed to do adequately. The theory has accounted for

feedback in the sense that the program has been seen to be a

hybrid system assembled from both open and closed loop

processes (Schmidt, 1988). Nevertheless, the theory has

neglected two important aspects of feedback. Firstly, the

theory has ignored the way in which skilled movement is

characterized by a coordination of movement of the various

joints. Such an integration of body parts requires that

information about the relationships amongst the various

joints be used in motor control. Several authors have

grappled with this problem (e.g. Abbs, 1984; MacKenzie &

Marteniuk, 1985; Tuller et al., 1982). In a study on

movement coordination during insect flight, Altman (1982

(cited in MacKenzie & Marteniuk, 1985)) discovered that

afferent input from various parts of the body of the insect

is involved in modulating the efferent output to the wings.

This gives evidence of the way in which movement at one

joint can involve an integration of information from various

joints.

Secondly, the theory has not accounted for the way in

which the overall duration parameter value is determined nor

the way in which it is assigned. In a computer program, it

is the programmer who both determines and assigns the

parameter values. Can we assume that a similar process is

occurring in humans? If we do, we are left with a little

computer programmer in our head assigning parameter values to the motor programs that control our movement. This is simply an homunculus theory which serves to explain nothing. The crucial question of the way in which feedback interacts with the program in timing control has been relegated to the realm of the homunculus. Because a computer does not have that dynamic interaction with its environment, that is characteristic of all living organisms, the computer metaphor can be both limiting and misleading. It is questionable whether the metaphor of a program is appropriate for use in explaining human movement (Carello et al, 1984).

Tracking studies provide an experimental context in which the contributions of feedback to timing control can be examined. In tracking (and other tasks involving an interaction with the environment) there are at least two forms of relative timing that can be identified:

1) relative timing within the response itself; and

2) the timing of the response relative to the stimulus. Feedback and feedforward mechanisms are involved in this second form of timing. In pursuit tracking, the two forms of timing influence one another, for, with a predictable stimulus, the better the subject's internal relative timing, the better a subject will be able to time the response relative to the stimulus (Pew, 1974). In the case of tracking, subjects seem to be using feedback to determine the immediate duration rather than the overall duration.

Gentner (1987) in his criticism of the proportional duration model has pointed out that one of the most remarkable characteristics of skilled motor behavior is its adaptability and flexibility. If flexibility is a characteristic of skilled behavior then it would seem obvious that feedback is being utilized in its control. The work of Abbs and his colleagues (Abbs et al., 1984) has illustrated this point. They found that when the lower lip was perturbed during speech, there was an adjustment to the perturbation in both the upper and lower lips. The adjustment in the upper lip served to preserve the speech objective of the utterance. In order to respond to a perturbation in this way a motor program must utilize feedback and feedforward mechanisms. This example of skilled motor activity illustrates the way in which feedback can be closely integrated with motor program execution.

Current motor programming theories have de-emphasized the importance of feedback in timing control. This may be one of their major flaws. Gentner has used this criticism to reject the proportional duration model. However, it is possible that the proportional duration model is consistent with a mode of motor control which involves feedback. Relative timing may characterize such closed loop skills as tracking. There has been evidence for this in studies by Franks & Wilberg (1982). In this study, as learning progressed the phase angles of the frequency components approached those of the stimulus such that the relative

timing of the response became identical to that of the stimulus, whereas the overall duration of the waveform varied, and tended to be longer than that of the stimulus.

The focus of the present study is learning. Few of the studies on invariant relative timing have given extensive enough practice to address the question of learning, nor have they given sufficient practice for subjects to develop a motor program (if one exists). It seems that one of the blind spots for many of those involved in traditional motor control research and theorizing has been the lack of consideration of movement ontogeny and learning. In such a context, the problem of insufficient practice is hardly surprising. Even learning researchers such as Gentile (1972) have argued that we must move away from motor learning into motor control until we have a better understanding of the "mechanisms underlying movement control". But as Reed (1988) has pointed out, it is in studying learning itself we can gain a better understanding of control. Arguments such as Gentile's are in some sense reductionistic. Because most studies on relative timing have avoided the question of the ontogeny of the motor program, little practice has been given. But if one considers the motor program in light of ontogeny, one is forced to question whether a motor program can be developed in 20 trials. With such insufficient practice, it is not surprising that the invariance that is deemed to exist within the program has not been found. Subjects have not

been given sufficient time to develop that invariance.

Also most studies on invariant relative timing have been based on the premise (with the exception of Armstrong's study) that invariant relative timing operates in a context in which a continuous interaction with the environment is not important, and have thus postulated a motor program which functions in a primarily open-loop fashion in terms of its timing control. As I have argued above, there are problems with this assumption.

In chosing a tracking task for the present study, the intention was to investigate the human-environment relationship during learning. Most of the studies on invariant relative timing have neglected this relationship by chosing tasks in which there is no continuous interaction between human and environment. The present study was designed to investigate the development of relative timing. By studying relative timing in a tracking task, it was possible to gain an understanding of the contribution of feedback in timing control.

In this review on learning, I have put focus on the question "what is learned". This is an essential question with a long history in the fields of psychology and motor behavior. One of the answers to this question, that has been discussed herein, is that humans learn the relative timing of a movement. However, the view of learning that has been put forward in the present paper, is different than that behind most of the research on relative timing, in that

it emphasizes organization rather than representation. In this view, as has been suggested above, parallels can be drawn between processes of living systems (such as morphogenesis) and processes of learning, in that both involve the evolution of the organism toward a more complex state of organization. Though learning is itself a process that occurs in living systems, it has often been considered as a "higher" function that is somehow removed from the rest of the biological world, and therefore not governed by the same laws. This assumption is based on a dualistic view of the human in which mind and body are seen as separate entities. In contrast, the view of learning put forward in this review has been one in which learning is seen as a process rooted in biology, rather than one removed from it.

APPENDIX B

PILOT STUDY

INTRODUCTION

> Indeed, if the nervous system does not operate - and
> cannot operate - with a representation of the surrounding
> world, what brings about the extraordinary functional
> effectiveness of man and animal and their enormous
> capacity to learn and manipulate the world? *Maturana &*
> *Varella (1987, p.133).*

A simple but essential question for those who seek to
understand learning is "What is learned?". This question
has been central to psychology since the inception of
behaviorism in the 1930's (Gibson, 1969; Weimer, 1977). One
answer that has been put forward invokes the development of
some kind of memorial (or central) representation. Within
the area of motor learning, this central representation has
been described in many different ways and has been given
many different labels such as: schema (Bartlett, 1932;
Schmidt, 1975), image of achievement (Pribram, 1971), and
motor program (Keele, 1975; Schmidt, 1988). Although the
historical development of these concepts has been associated
most often with open loop control processes, the role that
feedback plays in this learning process cannot be
underestimated. Indeed, Marteniuk and his co-workers
(MacKenzie & Marteniuk, 1985; Proteau, Marteniuk, Girouard,
& Dugas, 1987; Proteau, Marteniuk, & Levesque, 1988)
believe that **what is learned** are the developing
relationships between the action and the information that is

produced as a consequence of such actions. It is not the intent of this paper to pursue the centralist-peripheralist debate but instead to address the question of **what is learned** via the concept of organization, in such a way as to marry both feedback and representation. But, first let us start by arguing that organization is perhaps a more appropriate term to use than is representation.

The notion of representation, as it is generally conceived, inevitably leads to the problem of 'higher authority' (Carello, Turvey, Kugler, & Shaw, 1984; Meijer, 1988; and Reed, 1988). Maturana & Varella (1987) have proposed a solution to the problem of representationalism. Though learning may not involve representation of movement, it does involve changes in the brain, which bring about more skillful movement. Instead of conceiving of these changes as representations, they can be thought of as states of internal organization, which transform with learning, such that the interactions between the person/organism and the environment are different. Maturana and Varella suggest that we think of these internal changes in terms of internal correlations between sensory and motor processes. Consider an experiment conducted by Sperry (1945) as an illustration of this idea. A frog when presented with a fly in his visual field, will stick his tongue out and catch the fly. Sperry surgically rotated the eyes of a frog by 90 degrees. After the surgery, when he presented the frog with a fly, the frog stuck its tongue in a direction exactly 90 degrees

away from where the fly actually was. Thus the frog's

nervous system seems to have correlated sensory and motor

events, rather than to have represented the external

environment in its brain. Skilled human movement

encompasses a highly complex and integrated array of such

correlations, facilitating a highly efficient interaction

with the environment.

An alternative to the notion of representation, then,

is organization (which could involve both open and closed

loop control processes). Thought of in this way, learning

consists of shifts in internal states of organization.

There is evidence to indicate that both processes of

learning and processes of life involve organizational shifts

toward a higher order organization. Schrodinger (1944)

differentiates the living from the non living in terms of

order and entropy. "Living organisms" he writes "drink

order out of the environment" and in so doing, defy entropy.

As living organisms evolve they progress to higher order

levels of organization. Gentile & Nacson (1976) have

suggested that organization is also the basis of learning,

and there is behavioral evidence for such a process in motor

learning. Fuchs (1962) found that subjects developed a

higher level of perceptual motor organization, while

learning a tracking task and he based his progression-

regression hypothesis on the fact that subjects change their

control strategy over the course of learning.   This

experiment did provide evidence for a progression in

learning toward a higher order organization. With such a
progression it seems unnecessary to make recourse to any
kind of representation in order to explain learning.

A similar progression may be occurring in the
development of the coordinative structure. The coordinative
structure has been formally defined by Kugler et. al. (1980,
p.17) as "a group of muscles often spanning a number of
joints that is constrained to act as a single functional
unit". The coordinative structure incorporates feedback and
feedforward communications amongst the various joints and
body parts, such that these function as an integrated whole.
With learning, these feedback relationships become more
refined and organized. As an illustration of this consider
the comparison between the development of the coordinative
structure during learning and the process of morphogenesis.
Morphogensis involves ongoing and complementary processes of
differentiation and integration which lead to higher order
forms of organization. A similar process may be occurring
in the development of the coordinative structure during
learning. In the early stages of learning a motor task, the
body often moves in a rigid and undifferentiated fashion.
For instance, a novice batter will freeze out the degrees of
freedom by holding the body rigidly. An expert on the other
hand has learned the task appropriate constraints that
define the relationships amongst body parts (Tuller, Turvey
& Fitch, 1982). Whereas early in learning the relationships
are either random or rigid, later in learning they become

more defined and organized. Thought of in this way, the
coordinative structure is not a fixed structure, but rather
an ongoing process of differentiation and integration which
manifests in certain ways at certain stages of learning;
its development involves a progression toward a higher order
organization.

Such a systematic progression of organization in
learning a motor skill has been evident in tracking studies
(Franks & Wilberg, 1982; Jagacinski & Hah, 1988), and
movement reproduction tasks (Marteniuk & Romanow, 1983).
This progression appears to manifest itself through the
systematic acquisition of higher order component frequencies
of a movement. Over the course of learning, the movements
that are produced reveal a finer resolution. In the study
by Franks & Wilberg (1982), subjects were given extensive
practice in pursuit tracking a complex periodic waveform
composed of three component frequencies and then required to
reproduce the waveform pattern in the absence of any visual
stimulus or response information (a method of input blanking
first developed by Vossius, 1965). Early in learning,
subjects were able to reproduce only the general features of
this complex movement pattern. Their response contained the
major fundamental frequency of the stimulus, and thus was
only an approximation of the original. Only after long
periods of practice did the subjects gain an overall mastery
of the whole waveform and begin constructing the details
that were inherent in the stimulus. This was achieved by

the addition of higher order harmonics to the response
waveform, suggesting that people may learn and organize
movement in terms of component frequencies.

The hypothesis put forward was that skilled performers
can produce a response that closely maps the criterion
movement and therefore reduces the reliance of the system
upon its feedback control processes. Few corrective actions
need to be undertaken if the response is detailed and
accurate. However, novice performers that produce only a
limited but general approximation of the criterion need to
invoke the feedback and feedforward processes more
frequently in dealing with details of the movement.
Although this hypothesis was considered plausible given the
data, the subjects' responses were only submitted to a
Fourier analysis during the input blanking stage of the
experiment, and no account was taken of the subject's
response composition during the pursuit tracking phase of
the experiment, when both the stimulus and response cursors
were visible. Certain conclusions therefore, regarding the
superimposition of feedback control processes upon the
produced response during the pursuit tracking phase of the
experiment were at best only speculative.

The present study was undertaken, therefore, to address
the general question of **what is learned** and the specific
hypothesis that the process of learning a pursuit tracking
task involves a nested process of response generation with
superimposed control. That is, in order to fulfill the

requirements of the task (maintain alignment between stimulus and response with zero lag) the subject must generate a movement. The observed error between the stimulus and this generated response is dealt with by a feedback control system that operates upon this error.

Several specific questions were addressed in this study. Firstly, it was felt that further evidence was needed to verify the hypothesis that subjects do in fact learn to produce the higher frequency components of a complex waveform during the later stages of skill acquisition. Secondly, in order to gain an understanding of the way in which feedback influences the expression of component frequencies over the course of learning, three input blanking conditions (which involved a manipulation of visual feedback) were introduced. These were conditions in which the stimulus was withdrawn, the response was withdrawn and both stimulus and response were withdrawn from the visual display. Thirdly, a retention test was given to the subjects. Subjects were retested after a retention period of three months in order to investigate the stability and longevity of their tracking ability, and their ability to reproduce the learned waveform. If subjects learn to produce complex responses by systematically adding higher frequency components to their response, are they also able to produce these same higher harmonics after a period of retention. Fourthly, at the time of the retention test, subjects were transferred to four waveforms which varied in

base frequency, and two waveforms which varied the phase angles of the component frequencies. The first transfer condition was given in order to test whether subjects learn a movement in terms of the relative timing of the response elements of the movement, or in terms of the overall duration of the movement. The second transfer condition was given in order to determine whether subjects learn movement in terms of component frequencies or in terms of topological features. In this condition, the transfer waveforms are composed of the same component frequencies as that of the training waveform. In varying the phase angles of these component frequencies one creates a waveform with different topological features

METHOD

Subjects

Four university students with a right hand preference and no motor or vision deficits received course credit for their participation in this study. None of these subjects had previous tracking experience.

Task

Subjects were required to move a joystick which controlled a response cursor (point light display) on an oscilloscope screen. The subject's task was to follow a stimulus cursor (point light display) which appeared

directly above the response cursor on the screen and moved
in a series of horizontal movements across the screen.
Subjects sat at a table with their right forearm comfortably
supported. The oscilloscope screen was placed 50 cm in
front of them at a visually subtended angle of 11.4 degrees.
The subjects held the joystick between the index finger and
thumb. The wrist pronated and supinated in the coronal
plane while the joystick was being moved.

Apparatus

An industry standard plotting joystick (Hughes Aircraft
Company CONOGRAPHIC - 12 model 6110) with zero order
control, was adapted for use in the experiment by bypassing
its internal electronics. This joystick was fed by a
filtered 30 volt split power supply and connected to an
analog to digital converter (Techmar Labmaster), whose
daughter board was resident in an IBM Microcomputer. The
digital values given by the A/D converter of the Labmaster
ranged from +32767 (+10 volts) to -32768 digital values (-
10 volts), while the voltage range of the joystick was
approximately + 5 volts to -5 volts (zero volts being dead
center). The joystick was spring centered along the Y axis
and the X axis had free displacement, therefore only X co-
ordinate displacement was recorded. The potentiometer (a
Bourns number 3852A-282-103A), which transformed joystick
displacement into an electrical signal, had a resistance of
10,000 Ohms, and was linear (within one percent) throughout

the full range of joystick movement.

A computer generated stimulus was presented on the oscilloscope using a digital output equivalent to the digital input of the joystick. A second analog signal was used to maintain 1 cm of vertical displacement between the stimulus and response cursors on the oscilloscope. Response values were sampled every four milliseconds.

Waveform

The stimulus waveform was given by equation (1): $f(t) = A/2 + C \cos \omega t + C/2 \cos 2\omega t + C/4 \cos 4\omega t$. The period of one cycle of the stimulus was 2048 ms.

Procedure

I. Training Phase

This phase of the experiment took place over five consecutive days. Each experimental session consisted of 200 cycles of practice in pursuit tracking the stimulus waveform. This was followed by 10 test trials. The 200 practice cycles were broken down into four blocks of 50 cycles.

The **first** five test trials consisted of three phases: 1) **pursuit tracking** (PT) in which both stimulus and response cursors remained on the screen; 2) **partial input blanking I** (PIB1) in which only the movements of the stimulus cursor were shown on the screen; 3) **total input blanking** (TIB) in which neither the stimulus nor the response were shown on the screen.

Each of these first five trials consisted of 15 cycles of PT, followed by 7 cycles of PIB1, followed by 8 cycles of TIB. Data was sampled from the middle 2 cycles of each of these three phases.

The **second** five test trials consisted of two phases: 1) **pursuit tracking** (PT) as above; 2) **partial input blanking II** (PIB2) in which only the response was shown on the screen.

Each of these second five trials consisted of 15 cycles of PT, followed by 15 cycles of PIB2. Data was sampled from the middle two cycles of both phases.

II. Retention Phase

The same four subjects that were used in the training phase of the experiment returned to the laboratory after a period of 3 months. The task in this phase of the experiment was identical to that used in the first phase except that several different stimulus waveforms were used.

The subjects were given 200 cycles of practice on the original waveform (see Figure 1 and equation 1) and then tested for two trials of each of 10 waveforms described below. Each trial consisted of 10 cycles of PT, followed by 10 cycles of PIB1, followed by 10 cycles of PIB2, followed by 10 cycles of TIB.

Subjects were tested on their ability to track the following **ten waveforms:**

1) the original waveform from the training phase of the experiment at its original base frequency of 0.49 Hz.;

2) the original waveform at a base frequency of 0.31 Hz.;

3) the original waveform at a base frequency of 0.41 Hz.;

4) the original waveform at a base frequency of 0.61 Hz.;

5) the original waveform at a base frequency of 0.69 Hz.;

6) transformation of the original waveform with the component frequencies shifted out of phase by 90, 30, and 60 degrees and given by equation (2): $f(t) = A/2 + C \cos (\omega t + \pi/2) + C/2 \cos (2\omega t + \pi/6) + C/4 \cos (4\omega t + \pi/3)$.

7) transformation of the original 0.5 Hz waveform with the component frequencies shifted out of phase by 30, 60,

and 45 degrees and given by equation (3): f(t) = A/2 +

C cos (ωt + π/6) + C/2 cos (2ωt + π/3) + C/4 cos (4ωt

+ π/4).

8) an entirely new waveform given by equation (6): f(t) =

A/2 + 170 cos ωt + 65 cos 2ωt + 45 cos 4ωt

9) a randomly generated waveform varying in frequency

between 0.391 Hz and 1.904 Hz.

10) a waveform with the same amplitude and frequency values

as the original, but with those amplitude values

associated with different frequencies given by equation

(5): f(t) = A/2 + C/4 cos ωt + C cos 2 ωt + C/2 cos 4

ωt.

Data Analysis

Root mean squared error (RMS Error) was calculated on

the *pursuit tracking* data in order to determine response

accuracy. Poulton (1974) defines RMS error as the square

root of the sum of the squares of the error at each sampling

interval, divided by the number of sampling intervals. It

is given by the equation: RMSE = $[\Sigma (s-r)^2/ p]^{1/2}$, where

s is the stimulus value at time interval t, r is the

response value at time interval t, and p is the number of

intervals that the response is sampled over.

RMS error has been recommended by Poulton as the best

measure for evaluating the "overall *adequacy* of tracking"

(1974, p.38). A decrease in the value of RMS error scores

indicates that the subject has become more accurate and

precise in tracking, and thus is indicative of learning
(Franks, Wilberg & Fishburne, 1985; Poulton, 1974).

Variability of each subject's response was calculated
within each block of five trials for the pursuit tracking
phase based on a procedure from Franks, Wilberg, & Fishburne
(1982). Two cycles from each of the five trials were
sampled (for a total of ten cycles). The displacement-time
curves from these ten cycles were superimposed upon one
another in order to calculate a within subject variability
score. At each of the 512 sampling intervals a standard
deviation (sd) of the ten response displacements was
calculated using the following equation: S.D. = $[\Sigma$ (Mean$_r$
$-$ r)^2 / 10 $]^{1/2}$, where r is the response at a given time
interval and p is the number of intervals at which r is
sampled. The mean of these 512 sd's was used as the index
of within subject variability for a given trial. It also
allowed a profile of within waveform variability to be
calculated for each subject on each set of five trials, thus
indicating differential intra-subject variability throughout
the waveform.

Lead-lag index was used to determine the extent to
which the subject's response led or lagged the stimulus
during pursuit tracking. A cross-correlation coefficient
was calculated using the stimulus and the response waveforms
(each composed of 512 points), with the stimulus being held
constant and the response signal being advanced in time by
intervals of ten milliseconds. For each advancement of the

response signal a Pearson product-moment correlation coefficient between stimulus and response was calculated. The time at which the correlation between stimulus and response was greatest was used to determine the lead or lag of the response with respect to the stimulus.

The lead-lag index has previously been used as an indicant of the changing response strategies used by subjects during tracking (Franks, 1982; Franks & Wilberg, 1982). The limitation of this measure is that it only reflects the average lead or lag, rather than the specific location in the waveform at which the subject was leading or lagging (Poulton, 1974).

Harmonic analysis was used to analyze the response waveforms into component frequencies. The Harmonic analysis yielded the following information: i) the component frequencies of the response; ii) the amplitude values of these component frequencies; iii) the phase angle values of these component frequencies; and iv) the period of the waveform;

Bernstein (1967) was among the first to use harmonic analysis in the study of human movement. In the early 1900's, he performed experiments in which subjects were filmed performing various everyday movement tasks such as filing or hammering. The movement kinematics of the various link segments were then analyzed into component frequencies. More recently this analysis has been used by Green (1971) on RT data, by Franks & Wilberg (1982) in tracking, by

Marteniuk & Romanow (1983) on arm movement trajectories, and by Richardson & Pew (1968) in measuring stabilometer performance. In the present study, Harmonic analysis was used in order to determine the composition of the subject's response, during movement production, in all four feedback conditions (PT, PIB1, PIB2, and TIB).

The harmonic analysis was calculated based on a method described in Lowry and Hayden (1951 pp 324 - 328). The periodicity of the waveform (period = 2π) was determined using an autocorrelation. This waveform was then divided into p equal units and each of these points were labelled x0, x1, x2, ... xp, with their corresponding ordinate values being y0, y1, y2, ... yp. The trapezoidal rule of integration was applied over the period yielding the following equations: 1) $a_o = 2/p \pi y_r$

2) $a_n = 2/p \pi y_r \cos nx_r$

3) $b_n = 2/p \pi y_r \sin nx_r$

Equation 2 gave the harmonic coefficients of the cosine component of the waveform, while equation 3 gave the harmonic coefficients of the sine component of the waveform. The entire waveform was described by the equation:

$f(t) = A_o/2 + \pi A_n \cos n\omega t + B_n \sin n\omega t$

This equation was expressed in terms of a cosine function:

$f(t) = A_o/2 + \pi C_n \cos (n\omega t - \phi_n)$ where $Cn = A_n^2 + B_n^2$

ϕ_n represented the phase angle values which provided the necessary timing relationship among various harmonic components. These phase angle values were determined using

the following equation: tan ϕ_n = B_n/A_n

In order to test the accuracy of the harmonic analysis, the stimulus waveform itself was analyzed into component frequencies. These data were then resynthesized into a waveform which was compared to the original waveform by calculating the RMS error between the two waveforms. This produced an RMS error of 1.8 mm.

RESULTS and DISCUSSION

Pursuit Tracking

As expected, in the pursuit tracking condition performance improved with practice. Subjects became less errorful as measured by RMS error (see Figure 1). They also became more consistent in their response as measured by a within block variability score (see Figure 2).

In addition, the lead lag index as measured by a crosscorrelation function not only approached zero but became more consistent within each trial block as learning progressed. From the beginning, subjects were both leading the stimulus and lagging it, suggesting that subjects did not use a wait and move strategy in pursuit tracking. Rather it is likely that feedback was being used continuously to modify the subject's response (see Figure 3).

Figure 1.

Root Mean Squared Error as a function of practice for

training and retention days.

RMS ERROR

R
m
s

E
r
r
o
r

60

50

40

30

20

3
M
o
n
t
h
s

◇ phase
△ new

× .69

.49
.31
.61
.41

1   2   `3   4   5

Training Days

Retention

- .49 Hz wave   + .31 Hz wave   ✱ .41 Hz wave   □ .61 Hz wave
× .69 Hz wave   ◇ phase shifted △ new

* RMS Error 640 units = 10.0 cm

Figure 2.

Mean of 512 standard deviation values from the displacement

time profiles of 10 cycles of pursuit tracking for raining

and retention days.

Variability

Figure 3.

The standard deviation of the lead-lag index of the

subjects' responses relative to the stimulus over the five

training days.

Variability of Lead-Lag

* averaged over the four subjects

When subjects returned after a 3 month period for 2 further days of testing (retention days), it was found that subjects retained a level of performance equivalent to that of days three and four (experiment one) as measured by RMS and variability scores (see Figures 1 and 2).

In order to determine whether subjects learn relative timing, subjects, on these retention days, were transferred to various speeds of the original waveform. They maintained RMS and variability scores equivalent to those achieved on the original waveform for all speeds of the waveform, with the exception of the fastest waveform which had both higher RMS and variability scores (see Figures 1 and 2).

In order to determine whether subjects learn a movement in terms of its component frequencies or in terms of its topological features, subjects were transferred to two waveforms containing the component frequencies of the original waveform at different phase angles than the original. Performance on these waveforms was compared with performance on an entirely new waveform which contained different component frequencies. All three waveforms had different topological properties than the original. Performance on these waveforms was equivalent as measured by RMS and variability scores, indicating that subjects do not learn a movement in terms of its component frequencies but seem rather to learn a movement in terms of its topological features (see Figures 1 and 2).

Tracking under Various Feedback Conditions

The response waveforms from each of the four feedback conditions were compared and analyzed using an Harmonic analysis. With practice at the tracking task, subjects learned to produce a response (in all conditions) whose phase, frequency and amplitude more closely approximated that of the stimulus, than those of their earlier responses had (see Figures 4 - 6). This is in line with evidence from studies by Franks & Wilberg (1982) and Marteniuk & Romanow (1983).

In comparing the harmonic profiles of the subjects' responses with those of the stimulus, two aspects will be considered: one, how those frequency components that are contained in the stimulus are matched by equivalent components in the response, two, how those residual frequencies not contained in the stimulus (but expressed in the response) manifest in the four feedback conditions with different amounts of practice.

Subjects performed best in the pursuit tracking condition (as compared to the other feedback conditions) in terms of accurately producing the amplitude values of those component frequencies contained in the stimulus (Figures 4 - 6). With practice (i.e. by day five) the amplitude values of the response components became closer in value to those of the stimulus, and this was maintained over the three month retention interval. For the stimulus only condition, however (see Figures 4 - 6), such an improvement with

Figure 4.

The amplitudes of the harmonic components that comprised the response waveforms under the four feedback conditions on day 1.

Pursuit Tracking   Day 1

Stimulus Only   Day 1

Response Only   Day 1

Input Blanking   Day 1

Figure 5.

The amplitudes of the harmonic components that comprised the
response waveforms under the four feedback conditions on day
5.

Pursuit Tracking Day 5

Stimulus Only Day 5

Response Only Day 5

Input Blanking Day 5

Figure 6.

The amplitudes of the harmonic components that comprised the response waveforms under the four feedback conditions on the retention day.

Response Only   Retention

Input Blanking   Retention

Pursuit Tracking   Retention

Stimulus Only   Retention

practice was not evident. In comparing performance from the stimulus only and pursuit tracking conditions on day one, one finds that subjects seem to produce a better response in the stimulus only condition than they do in the pursuit tracking condition. This may be because early in learning, when subjects have a more limited attentional capacity than they do later in learning (Neisser, 1980), they perform better in a situation (like the stimulus only condition) in which there is less information to attend to. In the stimulus only condition subjects are only required to attend to the stimulus, whereas in pursuit tracking they are given information about the stimulus, the response and the error. Early in learning attempting to attend to these three forms of information seems to cause performance decrements.

The component frequencies of the response waveform during the response only condition compared more favorably to the stimulus than the input blanking condition. This was the case both early and later in learning. Visual information of their own response appeared to be critical in order for the subjects to produce an accurate approximation of the stimulus. When subjects return after a 3 month break, the conditions that show the greatest decrement in performance are those in which the visual response information has been removed. Thus it appears that the subjects may forget the correspondence between the visual information on the screen and the movement of their hand. This suggests that FB about ones own response is critical in

order to produce accurate movement. This is in line with Pribram's (1971) contention that movement is represented in sensory terms.

For all four feedback conditions, the residual noise in the response dissipated such that by day five the amplitudes of the residual frequencies were diminished, thus creating a response which more closely approximated the stimulus. This level of accuracy was carried over the 3 month retention interval in all four feedback conditions. In the pursuit tracking condition fewer residual frequencies were present as compared with the other conditions. And by day five virtually none of the higher frequency residual components were present in the pursuit tracking condition.

The fact that fewer high frequency components were found in the pursuit tracking condition than were found in the other conditions is contrary to what was expected. It was predicted that responses made in the pursuit tracking condition would contain more residual higher frequency components than the other conditions. It was thought that subjects would make more discrete corrections in pursuit tracking where they were given feedback about the discrepancy between stimulus and response than they would in other conditions in which this discrepancy information was not available. This prediction was based on the assumption that when feedback about error is available, subjects will respond to error by making discrete corrections. However it seems from the present findings that rather than making any

Figure 7.

Mean cycle duration (period) under the four feedback

conditions during training and retention.

Period of Training Wave

kind of discrete corrections, subjects used the visual
feedback to modulate their response in a more continuous
fashion.

As regards timing control, in the stimulus only and
pursuit tracking conditions, subjects produced movement
cycles that were of the same base frequency as those of the
stimulus. In the response only and input blanking
conditions, subjects produced movement cycles with lower
base frequencies (i.e. longer periods) than the stimulus.
Thus it seems that stimulus information is important in
determining the overall timing of a movement cycle (see
Figure 7). It seems from the present results that
the closed loop processes of response modification are
utilized in determining absolute (or immediate) timing.
This process of response modification is utilized early in
learning in the pursuit tracking condition, as well as late
in learning in the response only condition, such that the
absolute timing of the subjects response becomes identical
to that of the stimulus. When neither stimulus nor response
information are available to the subject the overall
duration of the subject's response is typically longer than
that of the stimulus. Thus feedback from the environment
seems to be important in determining absolute timing. Early
in learning stimulus information is necessary, whereas late
in learning response information is sufficient.

The present evidence indicates that subjects develop
some kind of organization of movement in which there seems

to be, as Bartlett (1932) has suggested for his schema, an interplay between FB and the schema itself. The movements from this study that were reproduced from memory also exhibited certain systematic distortions. This is in line with Bartlett's (1932) studies on memory in which he found that in recalling stories subjects would distort the details to fit their own cultural context.

More recently research on memory for spatial locations (Tversky, 1981) illustrates that in recalling geographical locations subjects make systematic distortions of space. For example, when subjects are asked to recall the location of Miami which is on the east coast of North America relative to Lima which is on the west coast of South America, they distort the relationship of the two continents putting South America directly south of North America. Thus though Miami is in fact west of Lima, people think of it being east of Lima.

This kind of distortion is also found in the brain's sensori-motor homunculus. A similar process may be occurring in the reproduction of the waveforms in this study. That is, in the input blanking condition the locations of the reversals and the changes of speed seem to be systematically distorted in space during movement reproduction or "memory".

The hypothesis that subjects systematically acquire the component frequencies of a movement was not supported by the present data. Rather in this study, subjects seemed to

systematically diminish the residual frequencies over the course of learning. It is possible that the progressive acquisition of component frequencies previously found (Franks & Wilberg, 1982; Marteniuk & Romanow, 1983) was task specific in the sense that both these studies used a large amplitude movement which involved the whole arm. The present study on the other hand used a smaller wrist movement.

APPENDIX C

KINEMATIC PROFILES INPUT BLANKING DAY 15 (BEST RMS)

S1D15W1 CYCLE 5 INPUT BLANKING, RMS: 68 SHIFT: 4 4ms points

s2d15w1 CYCLE 4 INPUT BLANKING, RMS: 40 SHIFT: -1 4ms points

s3d15w1 CYCLE 5 INPUT BLANKING, RMS: 84 SHIFT: -9 4ms points

s4d15w1 CYCLE 3 INPUT BLANKING, RMS: 45 SHIFT: 5 4ms points

s5d15w1 CYCLE 4 INPUT BLANKING, RMS: 33 SHIFT: 3 4ms points

s6d15w1 CYCLE 1 INPUT BLANKING, RMS: 52 SHIFT: -1 4ms points

APPENDIX D

KINEMATIC PROFILES INPUT BLANKING DAY 15
VARIABILITY AMOUNGST THE FIVE CYCLES

S1D15W1 INPUT BLANKING

S2D15W1 INPUT BLANKING

S3D15W1 INPUT BLANKING

S4D15W1 INPUT BLANKING

S5D15W1 INPUT BLANKING

S6D15W1 INPUT BLANKING

APPENDIX E

HARMONIC PROFILES DAY 15 (W1 — W7)
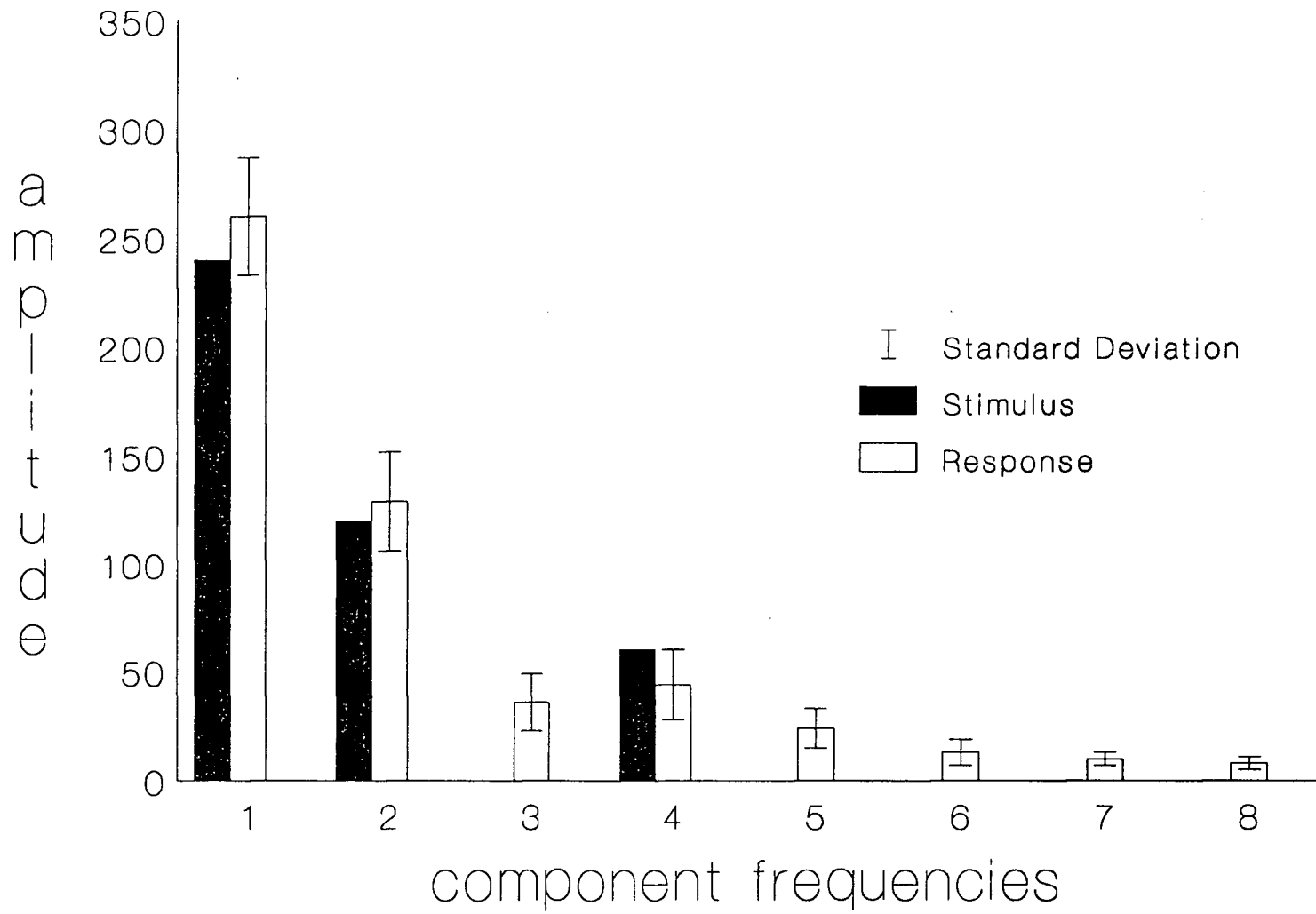
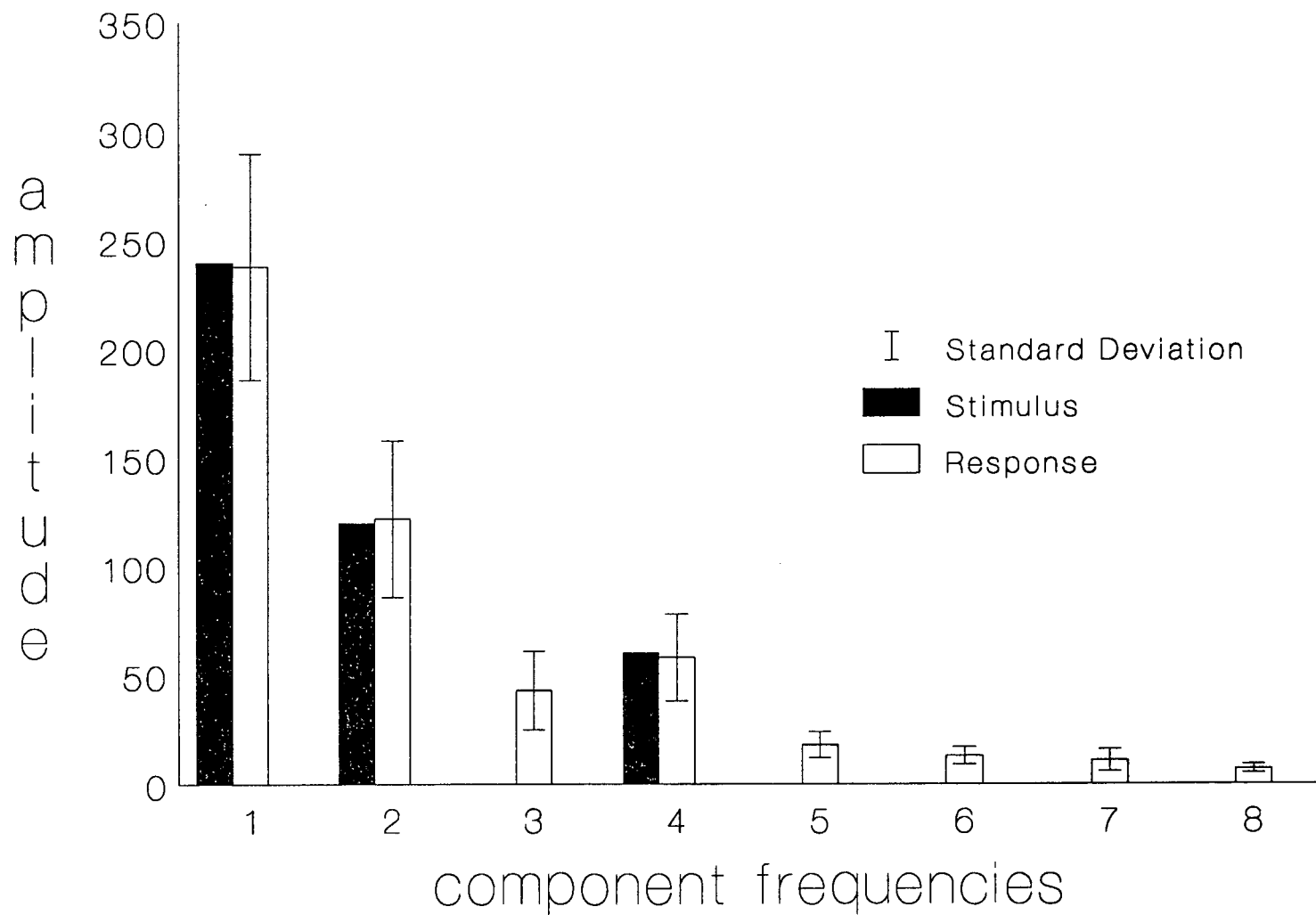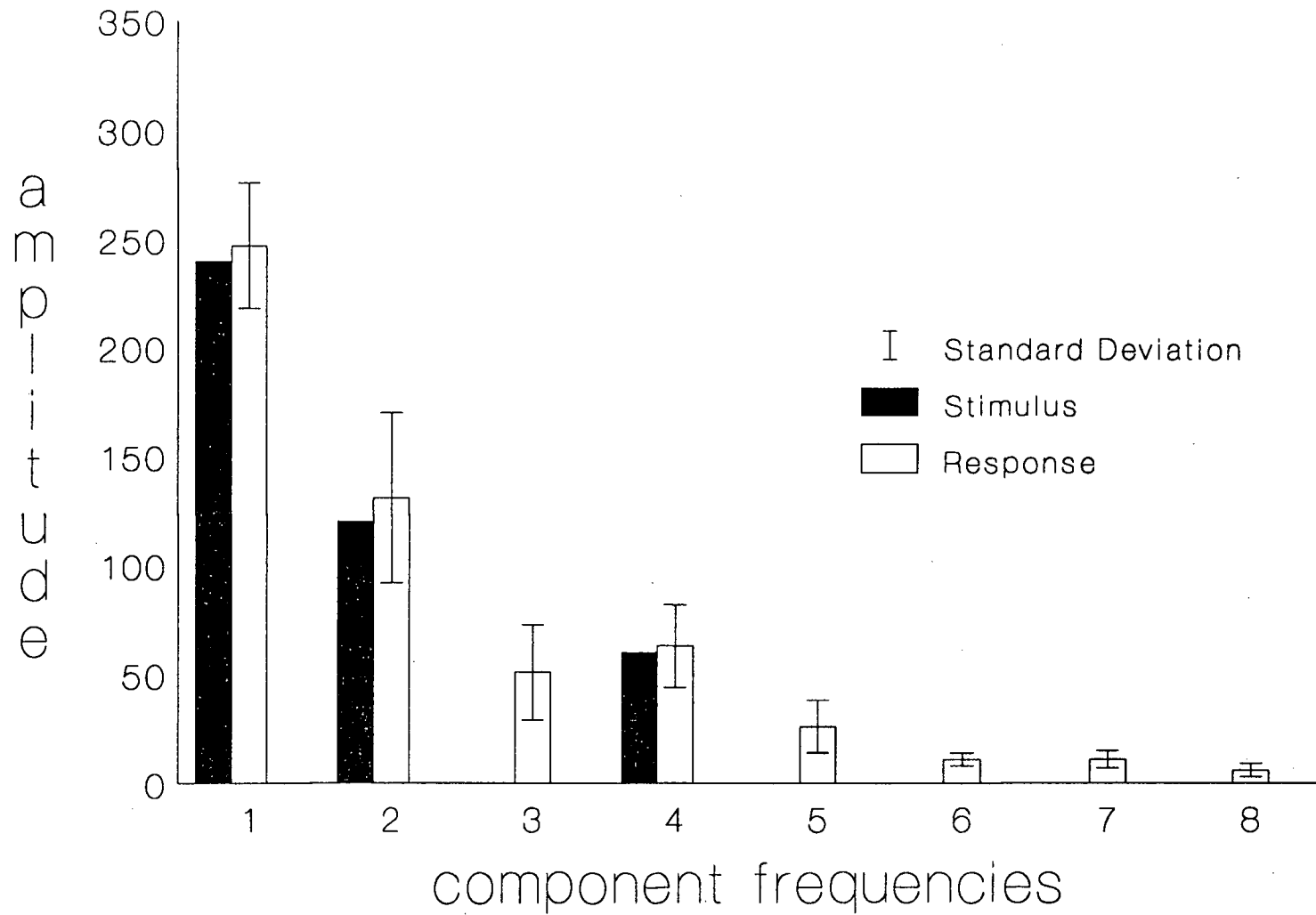Day 15 Wave 1

Day 15   Wave 2
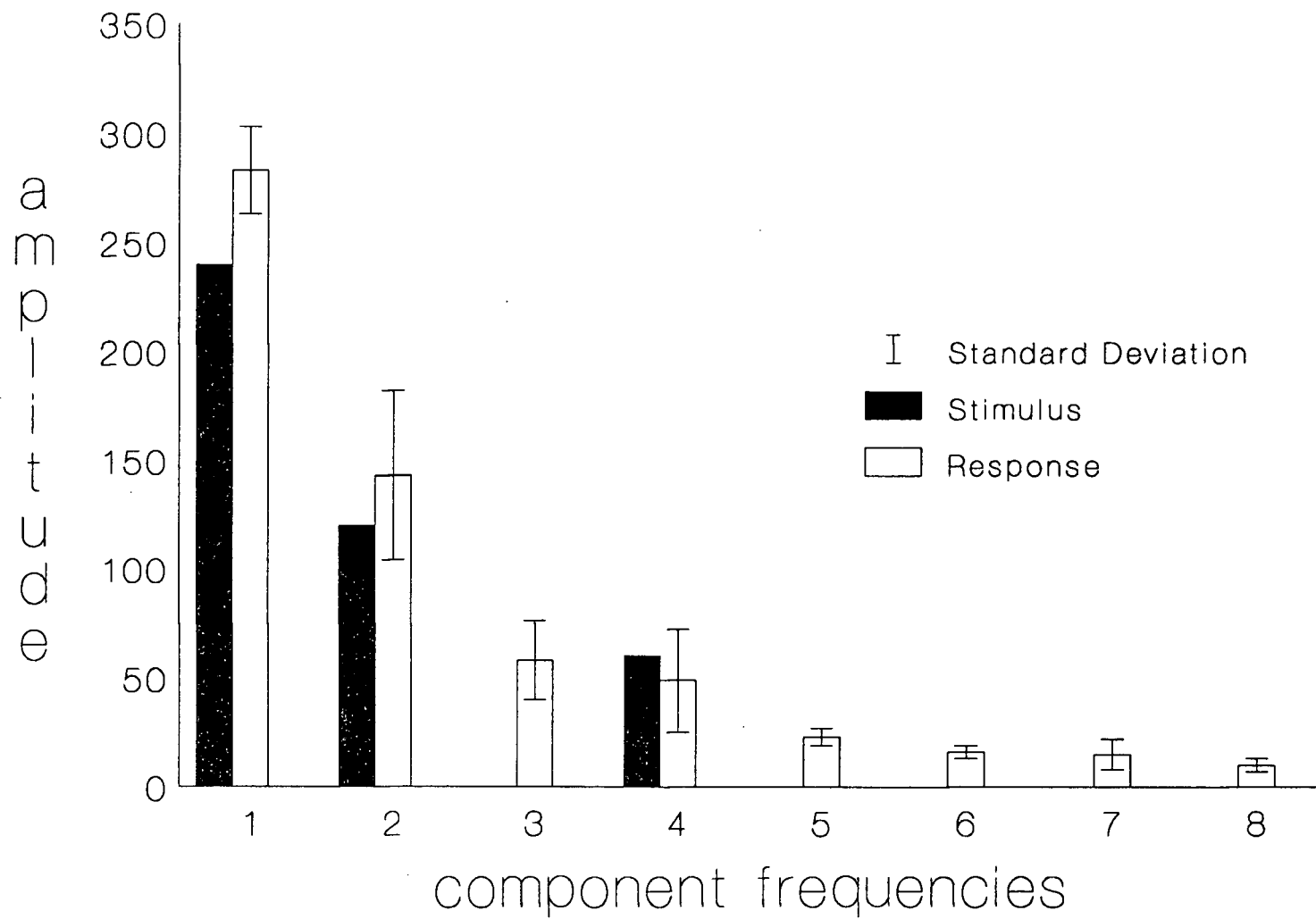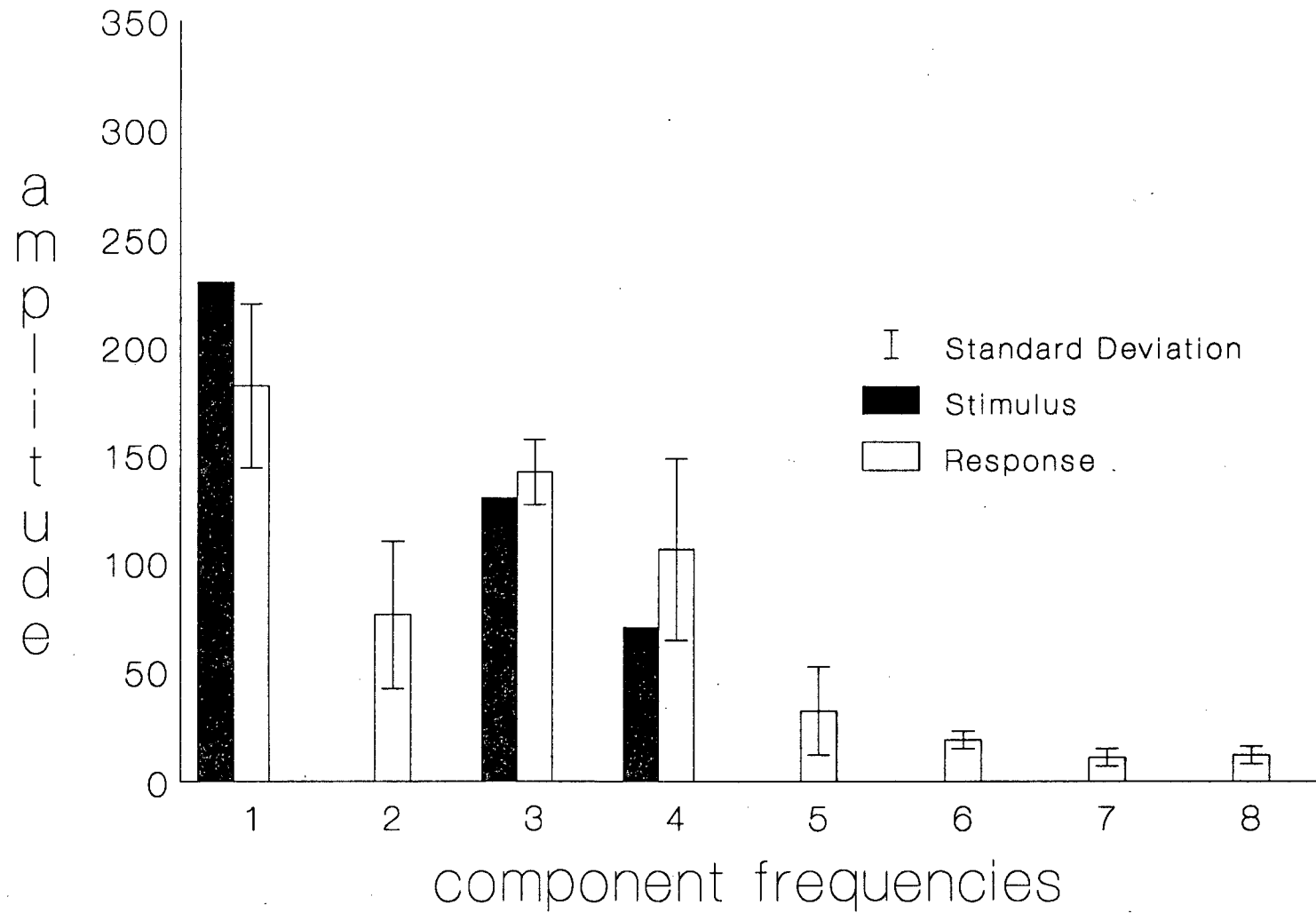
Day 15   Wave 3

Day 15   Wave 4

Day 15   Wave 5

Day 15   Wave 6

Day 15   Wave 7

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