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REGULATING TEMPO IN A CONTINUATION FINGER-TAPPING TASK

BY

ARTHUR ALLEN LITTLE

A DISSERTATION SUBMITTED IN PARTIAL FULFILLMENT OF THE

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Abstract

It is well known that people can produce regular rhythms, such as clapping or finger tapping—what is not well known is how such rhythms are maintained over time. One of the simplest activities to measure human rhythms is “continuation finger-tapping,” in which subjects are first asked to copy an audible rhythm by tapping along with their finger, and then attempt to maintain that tapping rate after the pacer tones stop.

The purpose of this study was to learn more about how tempo is regulated in continuation finger-tapping. In this context, "regulated" refers to the rules, both empirical and hypothetical, that govern the maintenance of a uniform tapping rate. The method used in this study was to determine whether there was evidence of two strategies for regulating rhythms: 1) Subrange/tapping style, and 2) Targeted drift-and-correction. Both archival and new data were analyzed for this research.

The first phase of the study was to determine whether at least two distinct subranges of tapping behaviors exist, and whether subjects used different tapping strategies for each subrange as reported in Vaughan, Matson, & Rosenbaum (1998). Two different variables were analyzed for the subrange/tapping style phase of the study: Duty Cycle (normalized time-on-target) and Velocity (force upon target).

The second phase of the study was to determine whether the subjects used a “target-sweeping” strategy to maintain a steady rhythm for their tap intervals (IRIs). In such a process, they would introduce continual, small negative biases (“drift”) which would then be countered by occasional, larger positive corrections. If this regulatory

method were used to maintain an average rhythm, there would be evidence of bimodal symmetry in the distributions of the IRI First Differences.

The first main finding is that Duty Cycle and Velocity change continuously as a function of ISI. This finding stands in marked contrast to two hypotheses that were plausible prior to this research. The first hypothesis was that duty cycle might have been constant, which would suggest that the hand motion for finger-tapping is a very simple process, in which all elements are "scaled" up or down proportionately to match a particular tempo. The data suggest rather that the pattern changes with the rate, but the change is very orderly, resembling a smooth quadratic function. The second hypothesis that was plausible before this study was that of discontinuous change. Discontinuous change had been suggested by Vaughan's terms "elastic" and "intermittent", which were two hypothesized regulatory styles for fast and slow tapping respectively. The data suggest that a sharp distinction between these two styles is not useful, because as ISI changes there is a gradual rather than an abrupt transition.

The second main finding is that distributions of IRI First-Differences do not conform to the prediction of a simple drift-and-correction theory of tempo regulation. Instead of a bimodal distribution, with one component representing numerous little "drifts" and the other representing a few bigger "corrections", we see a variety of distributional shapes, most of which are unimodal.

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Chapter 1: Introduction

“...since time sets its own tempo, like a heartbeat or an ebb tide, timepieces don’t really keep time. They just keep up with it, if they are able.”

--Dava Sobel, Longitude

Our sense of the passage of time is defined by changes that we observe in our world. These changes may appear to be instantaneous or they may take place gradually, but in any case, people are aware of the progression of time.

Far from being merely passive time detectors, people also possess the ability to control the timing of our behavior to adapt to external events. Our temporal control is in evidence over an extended time span, ranging from sub-second intervals to intervals that may last for decades. In short, we perceive time, and our actions keep up with time...if we are able.

Rhythm is a special case of such changes that we can perceive or produce. A rhythm is a set of regular changes in state that recur over time. One example is a musical tempo of 60 beats per minute, in which the change from non-beat to beat (the state change) repeats once per second.

Most people can perceive and generate simple rhythms without apparent effort, and our ability to do so is manifest quite early in human development (Thelen, 1996). Yet the underlying neural mechanisms that support time perception and timing behaviors are not well understood. Some information about human timing capacity can be inferred from constraints on performance that emerge when people are engaged in

timing-related activities. The most prominent such constraint is that human timing is limited to a certain range of oscillations.

Some rhythms are too rapid for humans to distinguish, much less produce. For example, vibrations in excess of 20,000Hz are typically unheard by the human ear, although they may be perfectly audible to other creatures (Woodworth & Schlosberg, 1954). Other rhythms can be so slow that their state changes may not even be recognized as being part of a series. For example, geophysical or climatic rhythms may take hundreds or thousands of years to complete a single cycle.

Timing research takes place between such temporal extremes, and even within the limited human range of rhythmic timing, researchers are presented with many practical challenges. For example, consider a range of rhythms that is well within human rhythmic timing capacity: rates ranging from four beats per second to one beat every hour. This range of intervals (0.25 seconds to 3600 seconds) spans four orders of magnitude. Precise and accurate measurement of any user-produced intervals across the full extent of this range is a non-trivial task, practically speaking. Therefore, most timing studies limit themselves to a still more restricted range of intervals.

In the study of human timing, one of the simplest tasks that requires both time perception and time-aware behavior is the basic task of copying a steady rhythm by tapping along with one's finger. In a concert, this behavior is frowned upon; in a laboratory, it is called synchronous tapping. If one maintains the rhythm after the original source has ended, it is called continuation tapping.

Continuation tapping is an accessible and readily-measured type of time-based behavior. In and of itself, learning how continuation tapping is regulated may be of

limited value; however, an understanding of tapping regulatory mechanisms might well be extended to understanding other temporally-paced sequential behaviors (e.g., blinking, swallowing, walking, or typing).

Chapter 2: Background

Continuation Tapping

The story of the continuation tapping (CT) task begins with its innovation by Lewis T. Stevens at Johns Hopkins University around 1885 to study human timing. Stevens (1886) said his process, “consisted...in impressing upon the mind intervals of time by means of a metronome, and in reproducing the same after the metronome had been stopped.” In a somewhat more detailed description, Collyer & Church (1998) describe the continuation tapping task as follows: “A person listens to a series of brief tones presented at a steady rate and begins to tap a finger in synchrony with them, one tap to each tone. The tones are then turned off, and the person continues to tap, attempting to maintain the original steady rate. The recorded behavior that occurs after the tones have ended is referred to as continuation tapping.”

That combination of synchronization tapping (with the target rhythm) and continuation tapping (after the target rhythm is withdrawn) makes up a complete trial. For each given trial, the tones that define the rhythm are isochronous; that is, they are sounded at a steady rate with equal intervals between them. A subject may perform several tapping trials during one day’s experimental session; often, the subject will tap at a different rate of speed for each trial (or block of trials) that makes up that session.

Tapping: Terms and Properties

Certain terms associated with continuation tapping will be defined at this point:

The Inter-Stimulus Interval or ISI is the time interval between the audio pacer tones that define the target tapping rate for a CT trial. The target tapping rate is

specified in taps per second (Hz), which is calculated as $1000/ISI$. The ISI value, which is expressed in milliseconds (ms), is chosen by the experimenter.

The Inter-Response Interval or IRI, is the measured interval between the subject's successive finger taps. Like the ISI, is expressed in milliseconds. Additional variables for analysis may be produced by partitioning the IRI into two complementary subdivisions:

Its first subdivision is the Down Interval or DI_1 , which is the interval measured while the subject's finger is actively engaged in pressing or touching the target. The DI is expressed in milliseconds.

Its second subdivision is the Up Interval or UI , which is the interval during which the finger is not actively pressing the target, and is expressed in milliseconds. By definition, the DI plus the UI equals the IRI, ($DI + UI = IRI$).

The Duty Cycle ratio (DC) is the actual proportion of the IRI that is occupied (or utilized) by the DI . Duty Cycle is the DI divided by the IRI, and for this study this ratio is expressed as a percentage: $DC \times 100\%$.

Drift is the trend of successive IRIs during the trial to become either longer (positive drift) or shorter (negative drift). Drift is operationalized (operationally defined) as the slope of a linear trendline fitted to the trial data.

Corrections are the compensatory changes in IRI tapping behavior during a trial that serve to counteract the prevailing drift. Corrections is defined in terms of relatively large IRIs, that are counter to the prevailing Drift. They are identified by examination of first difference values. A first difference is defined as subtracting the value of the current IRI from the value of the previous IRI—that is, $IRI_T - IRI_{T-1}$.

Impulse is the force with which the key is tapped. In this study, Impulse is operationalized as the Velocity value captured by the touch-sensitive keypad of a MIDI drum machine.

Musical Instrument Digital Interface (MIDI) is an industry-standard protocol that electronic musical instruments use to create and store music as computer data files. MIDI-compliant devices, such as drum machines, are readily adapted to capture timing data for continuation-tapping tasks.

The Oscillator Signature is a pattern of systematic deviations from exact ISI reproduction (Collyer, Broadbent, & Church, 1992; Collyer, Broadbent, & Church, 1994) that are rate-dependent. These deviations, both positive and negative, can be detected by plotting a subject's averaged IRI as a proportion of the target ISI rate over the ISI range. In its simplest representation, an Oscillator Signature is defined as "the function relating IRI (as a percentage: $IRI/ISI \times 100$) to ISI..." (Collyer, Boatright-Horowitz & Hooper, 1997). See Figure 1a

In several studies, when several subjects' oscillator signatures were averaged, the resulting plot has been a nonlinear "W"-shaped function that straddles the zero-bias axis (Collyer et al, 1992; Collyer et al, 1994; Collyer et al, 1997). Of particular interest to Collyer and colleagues, was when the plotted function crossed the center line (i.e., $IRI=ISI$) with a locally negative slope; they called such points Negative-Going Zero Crossings (1994). Such crossings were thought to be caused by a naturally-occurring attractor located near that ISI level. In practice, this behavior would occur when a subject was tapping too slowly at a shorter ISI, and then tapped too rapidly for the next longer ISI.

Tapping Research

Prior to Stevens' work with continuation tapping in the 1880's, other researchers had studied individual's ability to discriminate differential time intervals. According to E. G. Boring (1942), "...it was [Ernst] Mach who undertook the first experimental work, starting in 1860...[using] intervals ranging from 0.016 to 8.0 seconds, filling them with beats—that is to say, the observer heard first one series of beats and then another, being required to say whether the second series was longer or shorter than the first or of the same duration...He found the greatest sensitivity for an interval of 0.375 seconds..." Boring (1942) goes on to describe later work by Vierordt and Horing in 1864, who studied the ability to differentiate the lengths of "empty intervals," that is intervals defined and bounded by the beats of a metronome; they found the least amount of error at a rate of about 0.4 seconds. It should be noted that, to this day, continuation tapping uses this empty-interval technique for its target ISIs.

Despite decades of research, the fundamental timing mechanisms of continuation tapping task are still not well understood. However, previous studies have determined certain patterns of behavior that appear to be tempo-dependent. Within a limited ISI range of about four taps per second to about one tap per second, most subjects' average tapping is within about 3% (+/-) of the target ISI value. Furthermore, most subjects are unable to accurately reproduce rates much faster than about four taps per second (Collyer, Broadbent, & Church, 1992; Collyer, Broadbent, & Church, 1994).

Although subjects' averages tend to be accurate, the slight tapping errors that remain provide rich opportunities for studying human timing. These slight errors or

biases tend to be regular and systematic, as subjects are more accurate at some tempos than at others (Collyer et al, 1992; Wing & Kristofferson, 1973; Collyer et al, 1994; Collyer, Boatright-Horowitz & Hooper, 1997; and Hooper, 1998). Furthermore, a specific subject's characteristic pattern of errors tends to remain stable over time (Collyer et al, 1994).

In terms of accuracy, it is still not known why subjects consistently reproduce some rates too fast, some too slow, and some with neither bias; nor why different studies have reported minimal error at differing rates of speed (Stevens, 1886; Grondin, 1992; Collyer et al, 1992).

In terms of variability, it was only recently that there was agreement on the rate at which tapping variability increased as the target ISI tempo increased (Collyer & Church, 1998; Wing, 1980). Some of this uncertainty reflects the difficulties of extracting signal from noise when observing innately variable organisms. As Newell and Corcos (1993) have observed,

Variability is inherent within and between all biological systems. The considerable differences that may be discerned among the motor abilities of humans is strong testament to this observation, as is the fact that it seems impossible for a given individual to generate identical movement patterns on successive attempts at performing the same task [italics added]. (p. 1)

Despite these difficulties, analyses of subjects' tapping reveal certain systematic patterns that provide some indication about how rhythmic behavior is organized. A prime example from Collyer & Church (1998) notes that, "The oscillator signature

suggests that the range from 175ms to 1000ms is divided into at least two subranges.” That observation initiated this study to investigate whether two (or more) subranges could be verified experimentally , and if the presence of such subranges reflect the actions of a like number of neuromuscular approaches/strategies to accomplish the continuation tapping task.

Degrees of Freedom

One major obstacle to knowing how people regulate continuation tapping is our own behavioral versatility. Physiologically, there are many ways to convey a fingertip to a target. This wealth of interrelated motor options was identified by Bernstein (1967) as the *degrees of freedom problem*.

Newell & Corcos (1993) describe the relationship between variability and excess degrees of freedom in repetitive human movement:

Human movement is an emergent property that arises from the harnessing of the many degrees of freedom of the sensorimotor system in the service of realizing a given task goal. The total number of system degrees of freedom that are coordinated and controlled in the execution of human movement is very large. Indeed, there is a progressive increase in the number of degrees of freedom as one shifts observation to a more micro level of analysis of the sensorimotor system, such as from joints, to muscles, to motor units, to cells. This large number of degrees of freedom...naturally affords variability in human movement and, more generally, in biological motion. Furthermore, the considerable redundancy of the sensorimotor system also leads to the

variability evident in repetitive attempts to realize a solution to a given task demand. These potential types and sources of variability contribute to variations in the output of the motor system. (p. 1)

According to Jordan & Rosenbaum (1989), the problem with this abundance of options arises from the fact that “the degrees of freedom of carrying out some task exceeds the number of degrees of freedom needed to specify the task,” and therefore there are multiple, redundant solutions to “the problem of finding specifications of values for the system’s degrees of freedom so that it performs the task as desired.” Jordan & Rosenbaum go on to describe three general methods to reduce the degrees of freedom problem:

1. Adding feedback to the control system to correct error.
2. Introducing *cost functions* to limit choice of action.
3. “Allowing the inherent dynamical characteristics of the limb...determine the trajectory.”

This study was undertaken to help determine if simple neurophysiological processes in conjunction with a simple targeting strategy regulate tempo by reducing excess degrees of freedom. Specifically, this study will attempt to determine if control activities associated with selective feedback, cost functions, and physiological dynamics can be detected in continuation-tapping.

Two Areas of Inquiry

This study is concerned with analyzing two concepts or areas of inquiry, associated with ISI subranges, which may be theoretically informative as regards tapping regulation:

1. Subranges: This first area of inquiry asks whether ISIs are categorical or continuous during continuation tapping. Another way to express this concept is to ask if a subject's distributions of produced IRIs are 'smooth' or 'lumpy' over their entire range. If their distributions are smooth (e.g., linear with no discontinuities), then there would be no evidence of subranges; however, if the distributions are lumpy or multimodal, then there is evidence of subranges, and—by extension—evidence for an associated tapping style. Performance on two variables, Duty Cycle and Velocity, are analyzed in the effort to determine the nature of these distributions, and to locate the boundaries of such subranges if their distribution appears to be categorical.
2. Drift and Correction: This second area of inquiry asks whether there is evidence that subjects demonstrate a consistent bias (accelerate or decelerate tempo) during continuation tapping, and whether—in conjunction with corrections—this process of drift could serve as a targeting heuristic. The two trial variables analyzed are magnitude of Drift, and the distributions of Corrections as operationalized as IRI first differences.

The next two sections will discuss these two topics at greater length. Note that although the primary activity of these mechanisms are thought to be associated with differing ISI subranges, they are not necessarily presumed to be mutually exclusive.

Subranges (Categorical vs. Continuous)

The Subranges issue concerns the two qualitatively-different tapping styles observed by Vaughan, Mattson & Rosenbaum (1998), who suggest that the choice of tapping style represents a fundamental trade-off between sparing computational

capacities (e.g., temporal comparison and decision making), and sparing physiological capacities (e.g., metabolic energy and muscle fatigue). According to Vaughn et al, the selection of tapping style is rate-dependent, and the two tapping styles—Elastic and Intermittent—are associated with two subranges of target ISIs.

These two tapping styles were observed by Vaughan et al (1998) when subjects were engaged in synchronization tapping at two contrasting ISI target rates (333ms and 2000ms). The authors suggest that the two differing tapping styles (Elastic Tapping and Intermittent Tapping) conserve different resources: 1) neural/cognitive, and 2) physiological/metabolic. Furthermore, these two tapping styles were distinguished from each another by their differing Collision Impulse and Down Interval values (Vaughan et al, 1998).

Elastic Tapping, the faster-rate method, is employed when there is not enough time to plan each tap interval (Vaughan et al, 1998). By stiffening the muscles of the forearm, hand, and finger, the limb can behave something like a tuning fork that has a resonant frequency determined by its rigidity (Vaughan, Rosenbaum, Diedrich & Moore, 1996). Conceptually, an Elastic Tapping strategy would be termed a “variable limit cycle” model of timing/tapping (Glass & Mackey, 1988).

Esther Thelen (1996), writing about motor development in infants, describes rhythmic kicking behavior in terms that are strikingly similar to the behavior described by Vaughan and his colleagues:

Typically, limbs are thought to move as a result of muscle contraction. But during natural movements, both gravity and inertial forces also contribute to the final pathway of the limb. The inertial forces result

because any limb segment is mechanically linked to other moving segments...[and] we found, in accordance with kinematic and EMG data, that in rhythmical kicking, while the flexion part of the cycle was initiated by active muscle contraction, the extension phase was passive, with gravity and inertial forces acting to pull the leg out and away from the body.

Thus, although the kicks had both temporal and spatial patterns, these patterns were not explicitly specified in the neural commands to the muscle. Rather the patterns were emergent from both the energetic input to the legs in the form of muscle contraction, combined with the gravitational context, and the springy and inertial properties of the legs. The leg movements can be compared to those of a simple physical spring with a mass attached. When people impart energy to the spring, it oscillates with a regular period and amplitude that depends on the mass on the spring and its stiffness. As long as we periodically impart energy, the spring will, in a sense, “keep time” by its regular rhythmic cycles, although there is no explicit clock in the spring itself or in the energy delivered to it [italics added]. (pp. 151-152)

This description of the mechanics of infant limb oscillations provides additional support for the premise that an elastic tapping style is an intrinsic behavior that could be called upon as needed to satisfy task demands. One should acknowledge, however, that the effects of gravity would be less of a consideration for finger tapping than for leg kicking.

From the perspective of metabolic efficiency, an Elastic Tapping style does not appear to be a particularly cost-effective solution to the task demand. To keep limb segments rigid, certain agonist/antagonist muscles need to be continually contracted, and then additional agonist muscles must be contracted rhythmically to “impart energy” to the system. According to Vaughan et al (1998), the Elastic Tapping strategy is thought to conserve real-time planning and decision-making resources, at the expense of metabolic resources such as energy expenditure and muscle fatigue. Furthermore, an additional benefit to Elastic Tapping is that timing pulses might not need to be strictly accurate, because an appropriately rigid limb’s resonant frequency could amend variations in timing signals. Therefore, even though the arm muscles must work harder, the Elastic Tapping style could prove to be the most efficient high-speed strategy for conserving central neural resources. We must also keep in mind that the human brain, which makes up only 2% of our body weight, uses about 20% of our body’s energy (Blakemore, 1999), so that by sparing neural resources, one spares metabolic resources as well.

Presuming that Elastic Tapping is associated with higher tapping speeds, then there must be physiological limits to the frequency range that this tapping style could reasonably serve. The fastest tapping speed for Elastic Tapping must be constrained by the limit of the limb’s ability to become sufficiently rigid, while still remaining responsive to timing pulses. For most subjects, this limit seems to be an ISI rate around 225 to 250ms; previous continuation tapping studies indicate that most subjects are unable to accurately duplicate or maintain such rapid rates (Collyer et al, 1997). The low-frequency boundary for Elastic Tapping would presumably be reached when the

arm muscles become so relaxed that the limb is no longer elastic. Since this predicted ISI boundary between the Elastic and the Intermittent styles is not currently known, a major goal of this study is to examine these data for an indication of such a boundary.

Intermittent Tapping, which is presumed to be associated with the slower ISI subrange, would provide greater temporal opportunity for central neural processes to plan and execute motor-timing pulses. According to Vaughan et al (1998) the efficiency of Intermittent Tapping is realized by initiating muscle contractions only when needed to create the finger tap—thus minimizing the physiological expense to the body. This strategy might best be called an integrate-and-fire model of tapping (Wing, 1980, Glass & Mackey, 1988).

The limits of the frequency range for Intermittent Tapping are rather different from the limits of Elastic Tapping. The fast-rate boundary for Intermittent Tapping would be reached when Elastic Tapping becomes the more efficient modality; however, the slow-rate boundary is undetermined, because a target time could be extended to any timer interval (milliseconds, seconds, minutes, hours, etc.).

Drift and Correction

Drift and Correction is a two-part strategy that a subject may use during a trial to regulate timing. The proposition that adequate overall tapping accuracy might be accomplished by introducing drift—deliberate error—coupled with counteracting corrections is not intuitively obvious, so some background and explanation is in order.

Reviewing the discussion of the degrees of freedom problem, we recall three general methods to reduce excess degrees of freedom: Method 3 was to modify limb kinetics, such that “the resulting system has dynamical behavior characterized

by...attractors corresponding to desired movement trajectories” (Jordan & Rosenbaum, 1989). The description of modifying limb kinetics corresponds closely to the Subranges/Elastic Tapping strategy proposed for rapid tapping rates by Vaughan and his colleagues (1998). However, this “tunable limb” method has less applicability to the goal of constraining degrees of freedom when regulating the slower-speed Intermittent tapping style. However, Method 1 (feedback and correction) and Method 2 (restrict choices) are still available and applicable to the process of regulating the slower tapping rates of longer ISIs.

Feedback/correction is the first method of constraining degrees of freedom, and is thought to be associated with the Correction aspect of this model of regulation. In the feedback/correction process, current IRI performance is compared to a standard and the results of this comparison directs changes in future performance.

Restricted choice is the second method of limiting degrees of freedom, and is thought to be associated with the Instrumental Drift aspect of the Drift and Correction question. At its simplest, a restricted choice decision rule for tapping rate might be: “All other things being equal, speed up a bit.”

When these two processes are combined, the resource-sparing capability of this model is greatly augmented. Producing IRIs with a small drift in a known direction decreases the subject’s decision-making needs, while simultaneously increasing the certainty of making the appropriate correction. Such a speed-up-and-reset strategy may well sacrifice the accuracy of individual IRIs in order to better regulate average IRI trial accuracy.

At these slower tapping rates, there is more opportunity for the subject to use their physical resources more sparingly; however, not at the expense of neural/cognitive resources which must be conserved as well. An under-appreciated aspect of the CT task is that finger tapping is not the most important of the subject's activities during the trial. In fact, the subject's central nervous system is engaged in innumerable parallel activities—many of which have greater survival utility than the process of tapping out a rhythm from memory.

The instrumental Drift/Correction main question proposes that the subject introduces a small bias to interval production, which decreases the neural processing burden, and increases the likelihood of a “correct” correction. To illustrate the advantage of this heuristic procedure, consider the more conventional alternative: Suppose that some neural/cognitive resources are required to examine each tap interval to determine if it was over or under target boundaries, and—depending on the result of that inspection—decide what action (e.g., speed-up, slow-down, do-nothing) to take for the next tap. All this measuring, comparing, and reacting must take place in real-time and appears to be an enormous processing expense for a task of dubious importance.

The Drift model suggests that a more efficient alternative to attempting to regulate the accuracy of each individual IRI is to settle for an average trial accuracy. Presumably, the natural world has relatively few sub-second activities critical to human development that would not be satisfied by performance that is within 2% of identity.

A simple, but effective heuristic to achieve “acceptable” trial accuracy without testing each interval's upper and lower bounds would be to introduce a small, directionally consistent bias, whose overall effects would be moderated by offsetting

corrections. Such a process is termed Instrumental Drift because this slight drift or bias could serve as the means to achieve the objective of increased precision, and when coupled with simple, univalent corrections, could serve to regulate tapping accuracy.

The underlying assumption is that human memory is better suited to making temporal comparisons to a short range of frequencies, rather than to a specific frequency value. If, for example, the target ISI is 500ms, then a comparison range might include perceived values of between 525ms to 475ms. In an outline form, this procedure could be as simplistic as the following pseudocode fragment:

1. Begin
2. Tap a New IRI that is Slightly Faster than the Previous IRI
3. Compare the New IRI to Memory of Range
 - If New IRI Is Not $<$ Range, Then Goto Begin,
 - If New IRI Is $<$ Range, Then Enlarge Next IRI & Goto Begin.

Specifically, Instrumental Drift is hypothesized to work like this: During the course of a trial, the produced IRIs, though initially similar to the target ISI value, would decrease slightly as the tapping rate increased. Since all drift is constrained to be negative, the amount of interval inspection would be reduced by one-half, because the comparison would not need to check both upper and lower bounds of each interval—only the lower boundary.

In addition to conserving comparison/computational resources, the Drift and Correction model can conserve Correction decision-making requirements as well, because—in the general case—the direction of a correction decision can be summarized in extremely simple terms as: “Do the opposite of the drift.” Such a correction would modulate the produced timing behavior, and might also serve to partially ‘reset’ the timing reference in memory.

Hypotheses and Predictions

SUBRANGES OF ISI

Hypothesis 1: People use a different tapping approach for fast rates (short ISIs) than they do when tapping at slow rates (long ISIs). Prediction associated with this hypothesis: The structure of the tapping data will show evidence of these separate subranges (elastic for fast-rate and intermittent for slow-rate tapping). These differences will be observable as discontinuous change, such as a step function, in Duty Cycle and Velocity values over ISI rates.

H1_{NULL}: The hypothesis for analysis states that people use the same tapping technique at all rates. Therefore, the prediction associated with this null hypothesis is that there will be no indication of subranges, and the changes in Duty Cycle and Velocity values will be smooth across ISI rates.

DRIFT and CORRECTION

Hypothesis 2: People use a targeting strategy for regulating produced IRIs by introducing a small negative bias (drift) into trial tapping. This negative bias is then countered by positive corrections. Prediction associated with this hypothesis: The trial tapping data will show evidence of an overall negative bias, moderated by less-frequent positive corrections. These two processes will be observable by the presence of negative slopes of Robust Resistant lines fitted to trial data, and as bimodal distributions of First Differences of successive IRI values.

H2_{NULL}: The hypothesis for analysis states that variations in trial IRIs are not systematic. Therefore, the prediction associated with this null hypothesis is that there

will be no indication of negative drift across ISI rates, and that histograms of IRI First Differences will not exhibit bimodal distributions.

Chapter 3: Method

Overview

This experimental study is a within-subjects design, in which participants performed the continuation tapping task at varying target ISI rates. The study consists of a collation of newly-collected data and a reanalysis of two previously-collected data sets. These three data sets provided continuation tapping data from an aggregate total of 32 subjects.

Data Sets

The archival samples were collected for studies conducted by Collyer et al, (1994), and by Collyer et al, (1997). In this document, those studies are called CT-94 and CT-97 respectively. The new data set, called CT-99, was collected to extend those previous studies in two ways. First, CT-99 measured an additional variable, Velocity, to compare to the findings of Vaughn et al (1998). Second, CT-99 presented three target ISI rates (1600ms, 1800ms, and 2000ms) that are slower than the slowest used in the CT-94 and CT-97 studies, but which are directly comparable to that of Vaughn et al (1998). The CT-99 data set was collected using techniques and apparatus closely modeled on those used in the CT-97 study (see Figure 2).

For the CT-94 data set, each session data file contains the event data (down timestamp and up timestamp) for a five-trial block at ISI levels ranging from 200ms to 875ms, in 25ms increments. To ensure that the data were comparable across the three data sets, this study used the CT-94 data ranging from 275ms to 875ms, in 50ms increments. Data from two subjects were judged to be so discrepant that they could

constitute a threat to internal validity, so those subject data files were eliminated from the data set to be reanalyzed (see Table 4). Each remaining file contains timestamps for two CT events: 1) “begin-finger-down” and 2) “end-finger-down.” All the IRI, DI, and UI values were calculated using these timestamp data. Each CT-94 file contains timestamp data to calculate 50 IRIs, and their associated DIs, and UIs. For 14 subjects tapping 50 CT intervals at 13 ISI levels in five trials, there were 45,500 each of measures (IRI, DI, UI, & DC) to calculate and analyze.

For the CT-97 data set, each MIDI data file contains the event data for a single trial at a specific ISI level. In the original data set, the target ISIs ranged from 175ms to 1000ms in 25ms increments. To ensure that the data were comparable across the three data sets, this study used the CT-97 data ranging from 275ms to 975ms, in 50ms increments. All MIDI timing information saved by the sequencer program was encoded according to a musical timebase. The length of a “beat”, the MIDI time unit, varies according to the ISI level produced, but a beat is constant in terms of its “tick” subunits—at 480 ticks per beat. That relationship is defined as $ISI/480$, and the quotient provides the coefficient that is used to convert MIDI timestamps to milliseconds.

Each MIDI binary file was converted to a text file using the MF2T (Van Oostrum, 1995) utility. A custom data-extraction program was created for the CT-97 and CT-99 data files to automatically make these conversions (see Listing 3). The session data files for one subject were not appropriate for analysis, so data sets from six subjects were reanalyzed for this study (see Table 4). Each CT-97 file contained sufficient timestamp data to calculate 27 continuation IRIs, and their component DIs,

and UIs. For six subjects tapping 27 CT intervals at 15 ISI levels in each of three sessions, there were 7,290 intervals and ratios (IRI, DI, UI, & DC) to calculate and analyze.

For the CT-99 data set, each MIDI data file contains the event data for 15 trials at ISI levels of 275ms to 975ms, in 50ms increments, and 3 longer (1600, 1800, and 2000ms ISI) trials. Each file was designed to record sufficient timestamp data to calculate 27 continuation tapping IRIs, and their associated velocity levels. Velocity values were collected by using a drum machine with a velocity-sensitive keypad as the input device. The tradeoff for gaining this velocity data was losing the “end-finger-down” timestamp information, which precluded any partitioning of the IRI into its DI and UI components.

Two of the 12 subjects in the CT-99 study did not press the keypad with sufficient force to register differential velocity levels, so their responses were not included in the velocity analysis of this study; however their tapping data was used for the remaining analyses. Therefore, for 12 subjects tapping 27 CT intervals at 18 ISI levels in each of two sessions, there were 11,644 IRIs and Velocity values to calculate and analyze.

Subjects

The CT-94 participants included 16 subjects (12 women/4 men, all students at URI) in the study Collyer et al (1994). Each subject participated in seven sessions of continuation tapping. Each session was made up of four blocks of unique ISI tempos, presented randomly. Each block consisted of five-continuation tapping trials at the same ISI level, which were recorded successively.

The CT-97 participants included seven subjects (1 woman/6 men, 6 students and 1 faculty member at URI) Collyer, Boatright-Horowitz, & Hooper (1997). Each subject participated in three sessions and each session was made up of 34 trials, one for each target ISI tempo. Each subject was both participant and investigator because all trials and sessions were self-administered

The CT-99 participants included 12 adult (over 18 years of age) subjects (7 women/5 men, 10 students and 2 faculty members at URI) during the Summer of 1999. Each subject was asked to participate in two sessions. Each session was made up of two practice trials and 18 data collection trials, one for each planned ISI tempo. The practice trials consisted of a “fast” ISI rate (333ms) and a “slow” rate (1400ms); these values were chosen because they were similar—but not identical—to the actual ISI rates used for the continuation tapping data collection. The order of the ISI presentations were varied by randomly assigning a subject to one of four presentation schedules (see Appendix C). Each presentation schedule listed the target ISIs as three blocks of six ISIs. The order of the sub-second ISIs were randomized, but the three longer ISIs (1600, 1800, & 2000ms) were constrained to each only occur once per block, as the last ISI presented.

Protection of Human Participants

Several precautions were put into place in order to protect the rights and the safety of the human subjects who participated in this study. First, it should be noted that the two reanalyses were performed on archival data sets (CT-94 & CT-97) that were themselves previously approved by the University of Rhode Island Institutional

Review Board (IRB). The experimental procedures used for the CT-99 data set were approved by the IRB in June 1999, prior to any data collection.

Additionally, the CT-99 data were collected according to accepted procedures and practices as defined by the American Psychological Association (1992). Each CT-99 subject/participant volunteered to take part in this study, and its goals and procedures were read to each subject (see Appendix A). At the end of their participation, they were ‘debriefed’, which consisted of stating to each subject, “There was no deception used in this experiment, and to the best of my knowledge, everything I told you at the beginning was accurate and complete.” Then each person was thanked again for participating.

Setting and Apparatus

For the CT-94 data set, “The subjects were tested individually in a quiet room while seated at a table and wearing headphones. Tapping was done with the index finger of the right hand. The subjects held the response box with the thumb and remaining fingers of the right hand while tapping. The box rested on a typewriter pad to prevent extraneous movement (Collyer et al, 1994).

All tone presentation and data collection were managed by an IBM PS/2 host PC (Collyer et al, 1994). The PC’s Input/Output data-capture card performed a dual role: It generated the pacer tones, and also measured the tapping/timing responses. The subjects did not tap their fingers on a physical switch; instead, they tapped on a small wooden tile mounted on the small plastic “response box.” The target tile was between and below “an infrared [LED] emitter and [phototransistor] detector mounted 4 cm apart ...” Collyer et al (1994). When the subject’s finger interrupted the path of the

infrared light, a signal was sent to the PC, which collated and saved these trial data as text files. The entire circuit latency (from light-beam interruption to acquisition at the PC) was reported to be less than .05ms .

For the CT-97 data set, the setting for this study was a dedicated lab in the Chafee Social Sciences building at the University of Rhode Island. All signals and timing were managed by a Gateway 2000 (i486 IBM PC-compatible) computer in an Microsoft Windows 3.1 environment. The Cakewalk Professional 3.0 MIDI sequencer program initiated MIDI signals that were translated by the Gateway's audio adapter card into pacer tones, which were relayed to amplified speakers. The subject tapped a key on a Casio drum machine, which was attached to the PC's audio adapter card by a MIDI cable. In this way, the music sequencer software simultaneously presented the stimuli tones and recorded the subject's tapping behavior. The temporal precision was reported to be about one ms at ISI of about 500ms.

For the CT-99 data set, the setting was an office in the Chafee Social Sciences Building at the University of Rhode Island. Subjects were placed at a desk, and the apparatus was before them on the desktop. They were seated on a swivel chair, and were encouraged to find a comfortable position with their dominant arm lying flat onto the desktop. The researcher read the same scripted instructions to each subject. Each subject was given two practice trials in order to assure that they understood the instructions, and that all equipment was working properly.

All signal generation and temporal data recording were managed by a Compaq Presario 1270 laptop computer running the Cakewalk Professional 5.0 MIDI sequencer (Hendershott, 1996) under Microsoft Windows-98. The subjects tapped on a "touch-

sensitive” keypad of an Alesis SR-16 drum machine. The drum machine was connected with MIDI cables to a Portman PC/P MIDI hardware interface, which in turn was connected to the computer’s parallel printer port. The audio tones generated by the Cakewalk Pro MIDI sequencer were sent from the computer’s “audio out” jack to powered speakers or to a pair of monaural headphones that the subject wore. All timing and velocity data were recorded by the Cakewalk MIDI sequencer. Other than having the capacity to collect velocity data, the CT-99 apparatus was very similar to the apparatus used in the CT-97 study. Like the CT-97 study, temporal precision was within one millisecond accuracy at an ISI level of about 500ms.

Independent Variable

The ISI (Interstimulus Interval) is the principal independent variable that is manipulated in continuation tapping experiments (Collyer et al, 1992; Ivry & Keele, 1989). An ISI is the time interval, in milliseconds, between the onset of one stimulus and the onset of the next stimulus in an isochronous series of stimuli, and makes up the “empty interval” devised by Vierodt and Horing in 1864.

Table 1: Variables Associated with Data Sets

Data set	IRI	DI	UI	Duty Cycle%	Velocity	RR Drift	Correction
CT-94	X	X	X	X	N/A	X	X
CT-97	X	X	X	X	N/A	X	X
CT-99	X	N/A	N/A	N/A	X	X	X

Dependent Variables

The IRI (Interresponse Interval), measured from the onset of one tap until the onset of its succeeding tap, has been the primary dependent variable in continuation tapping research (Collyer et al, 1992; Stevens, 1886; Wearden, 1991). Within the timing literature, the ISI is sometimes referred to as the Intertap Interval (Nagasaki, 1990) or Inter-Onset Interval (Repp, 1998). The series of IRIs produced during the CT trial represents the subject's effort to reproduce the ISI target rate without the auditory pacer stimuli.

The DI (Down Interval) is the interval that the subject's fingertip is pressing the target during an individual tap. A fraction of the IRI, the DI is also called the Dwell Interval (Vaughan et al, 1998).

The UI (Up Interval), which is the complement to the DI, is the interval that the subject's fingertip is not pressing the target; the Up Interval is also called the Back Interval (Vaughan et al, 1998).

The Duty Cycle ratio (DC) is the proportion of the IRI employed by the DI. In this study, the DC is defined and reported as follows: $DC = DI / (DI+UI) * 100$. Because the Duty Cycle is a ratio, representing the relationship between two quantities, it has the useful property of being "unit-free," which permits direct comparisons among

different levels of target ISIs. In this study, the primary application of Duty Cycle ratios is to determine if the Elastic and Intermittent tapping styles can be differentiated as reported by Vaughan et al (1998).

Drift is the within-trial trend of successive IRIs, and may be positive (“slowing down”), negative (“speeding up”), or zero (“no average overall change”). In this study, Drift is operationalized as a non-zero value for the Robust-Resistant line—a linear trendline fitted to a trial’s IRI data. Historically, a least-squares (OLS) regression line was used to determine drift. However, the least-squares procedure lacks “resistance to the excessive influence of a few atypical cases” (Hartwig & Dearing, 1979), which means that the typically small biases associated with continuation tapping could be masked or distorted by outlier values.

The Robust Resistant line, also called a Tukey line, is a straight line, traditionally fitted to a bivariate scatterplot to clarify the relationship between the variables. The Robust Resistant line uses as its endpoints the median values of the first one-third and last one-third of the trial data stream. As a visual summary of its underlying data stream, the robust resistant line is much less vulnerable to the effects of extreme data than is the least-squares regression line which is calculated by minimizing the squared distances from the mean (Hartwig & Dearing, 1979, Wilcox, 1998).

Corrections are the counterbalancing IRIs produced during a trial that serve to offset the prevailing trial drift. For example, if a subject’s tapping begins to speed up slightly during a trial, the subject may interject some longer IRIs to partially offset this trend. The presence and the effect of such countervailing correction(s) may be

determined by examining the number and the size of the first differences of sequential IRIs ($X_T - X_{T-1}$) for each trial of each subject.

The Velocity variable is a built-in property of every MIDI note that is recorded. For this study, the eight levels of velocity values were used to represent key pressure, since MIDI Velocity is used to define volume levels in electronic music (Rona, 1994).

Procedure

For the CT-94 data set, the procedure was to synchronize to a train of 50 audio stimuli, and then continue tapping, as described by Collyer et al (1994), “After 50 synchronization taps, there were no further pacer sounds. The subject’s task was to continue tapping at the same rate. The trial ended after 50 of these taps in the continuation phase without pacer sounds...There were 28 values of ISI, ranging from 200 to 875 ms in steps of 25 ms.” (p. 445).

For the CT-97 data set, specialized MIDI percussion files were “...prepared in the Cakewalk software for each value of ISI from 175 to 1000 ms in steps of 25 ms. When played, [the MIDI file] produced a series of 12 sounds...at the specified ISI.” These 12 pacer sounds made up the synchronization phase of the trial. After listening to the synchronization sounds, the MIDI music file was “played again in Record mode [and] subjects attempted to synchronize finger tapping...with the rate of presentation” upon the designated keypad of the drum machine (Collyer et al, 1997). When the 12 pacer tones were discontinued, the subject began the continuation tapping phase of the trial. Subjects were allowed enough time to produce at least 28 taps, and then an end-of-trial sound was signaled. Each subject completed three sessions, and all tapping data were captured by the Cakewalk v3.0 MIDI sequencer, and saved as individual MIDI

music files (Hendershott, 1994). After the sessions were completed, these MIDI files were converted to ASCII text files with the MF2T.EXE utility program (Van Oostrum, 1995).

For the CT-99 data set, 18 MIDI percussion files were created with the Cakewalk v5.0 MIDI sequencer software (Twelve Tone Systems, 1996) as target ISIs which were presented at each of two session's ISI values. These 18 ISIs were comprised of 15 sub-second ISIs (275 to 975 ms in steps of 50ms), and 3 longer ISIs (1600, 1800, and 2000 ms). These ISI values were chosen to permit direct comparisons to the overlapping ISI levels used in the CT-94/CT-97 data sets, and to the longer ISIs used in the Vaughan et al (1998) study. A session consisted of three blocks of six ISIs, chosen and presented in one of four previously-determined series, in which the order of the sub-second ISIs were randomized, but the three longer ISIs (1600, 1800, & 2000ms) were constrained to each only occur once per block. A trial consisted of twelve pacer tones for the synchronization phase, followed by an interval sufficient for an additional 30 taps in the continuation phase.

All of the data processing was performed on an IBM Aptiva 190E personal computer with the Microsoft Windows 98 environment. The software used for recording data, data extraction, timebase conversion, and analyzing this project is listed in Table 2. All MIDI files, programs, and macros were written by the author.

Table 2: Software Used for Study

Product	Type	Function
Cakewalk Pro	MIDI Sequencer	Present ISI stimuli and record timestamp responses.
MF2T	MIDI Utility	MIDI binary file to ASCII text file conversion program (freeware).
QuickBasic v4.5 Compiler	Procedural Language	Custom programs to extract/collate/calculate data from raw data (text) files
Excel 97 VBA	Macro Language	Custom macros to structure, convert, & condense data. and automate processing data files in Excel.
Excel 97	Spreadsheet	Spreadsheet application for data analysis, graphical output, and hosting macros.
WinBatch-99	Control Language	Batch processing of multiple data files sequentially (e.g., run MF2T on 36 files per command).
SPSS/Windows v9	Statistical Analysis	Statistical analyses, plots and graphs; .SPSS syntax files to transform data.
WinWord 97	Word Processing	Global text handling; documentation.

Chapter 4: Results

Data Preparation

All data files were collated into a standard format in which all continuation-tapping timestamp data were extracted into intermediate timestamp files. For the CT-94 files, which had been originally recorded in a text file format (see Listing 1), this was a relatively simple process of selecting and copying the appropriate data into new timestamp data files. By contrast, the CT-97 and CT-99 data of interest were recorded using MIDI timing protocols—a non-text file format; therefore, accessing their timing data required additional steps.

The first step was to translate MIDI files from their native binary format into a text file format (see Listing 2). This translation was performed by using a PC-compatible MIDI-to-Text utility called MF2T.EXE (Van Oostrum, 1995); a control language utility called WinBatch-99 (Wilson, 1999; Shamma, 1996) was used to automate this translation process. The second step was performed by a QuickBasic translation program written by the author that converted the MIDI 480-tick-per-beat time standard to milliseconds. This translation program (see Listing 3) also extracted the data of interest from the MF2T output files and saved them in text format as intermediate timestamp files.

Intermediate timestamp files consist of two columns containing the Up and Down timestamps, except for the CT-99 files which consisted of three columns: Up timestamp, Down timestamp, and Velocity of keypress. All intermediate filenames were coded by Data set (A=CT-94, B=CT-97, C=CT-99), Subject (01 to n), Trial (A-E) and ISI Level (0275-0875). For example, the filename C05A0825.DAT would be

parsed as follows: C = CT-99, 05 = Subject #5, A = Trial 1, 0825 = 825ms ISI, and the DAT suffix designates it as an intermediate timestamp file.

Each intermediate file needed to be structured and formatted identically, because each data set's intermediate timestamp file was imported into a custom Microsoft Excel spreadsheet template that automatically calculated all IRI variables for each tap, and also calculated the Robust Resistant Line slope, the Least Squares (OLS) Regression Line slope, as well as the First Differences, and variability (SIQR) statistics for each trial. For the CT-94 and CT-97 data sets, the spreadsheets calculated the DI, UI, and Duty Cycle ratios for each tap. For the CT-99 data set, the spreadsheets calculated descriptive statistics for the Velocity values.

The SIQR (Semi-Interquartile Range) was the preferred measure of dispersion in this study instead of the more commonly used standard deviation. This choice was made for much the same reason as electing to use the Robust Resistant line to determine slope; the SIQR is a more robust statistic and has a greater resistance to the distorting effects of extreme values. Similarly, for this study 20%Trimmed Means were used to calculate the central tendency of continuation tapping distributions, rather than the means. This choice was made because the arithmetic mean is sensitive to the effects of outliers and has reduced statistical power when used with a nonnormal distribution (Wilcox, 1998).

Data Screening

The initial data screening step began by running the Microsoft Excel Descriptive Statistics procedure on the measured variables for each subject at each ISI level for all three data sets. These descriptive statistics revealed certain anomalies in

the data (extreme values, data gaps, and singularities). An examination of these data files made evident that three of the 35 aggregated subjects data files were not collected in accordance with their experimental protocol. According to the file timestamps, one subject tapped 65 trials—with 100-taps per trial—in one all-day session, rather than on multiple, non-sequential days, which was the protocol used by the other subjects. A second subject's data disks were mislabeled in such a way that two of the subject's three sessions consisted of identical data. The third subject's data files included repeated instances of out-of-bounds data (e.g., IRI values of 25,000ms).

Whatever the source of the error, these irregularities rendered the data collected from these three subjects unreliable and misleading. Therefore, all CT event data for these three subjects were eliminated from further analysis. Table 3 describes these subject exclusions by data set. Note that four subjects in the CT-99 data set produced Velocity values that had zero variability, so these subjects' Velocity data were excluded from the Subrange/Velocity analyses; however, their IRI data were included in the Drift/Correction analyses.

Additionally, a few of the recorded IRIs were about twice as long as the expected interval because of a missed tap; these IRIs were replaced by an interpolated value—the expected value of the target IRI and the two adjacent IRIs. Altogether, the total of missed-tap data made up slightly less than 0.2% of the aggregate of all three data sets. All other cases of missing data were minor, and were dealt with using pairwise deletion (SPSS Inc, 1999).

Table 3: Subject Exclusions

Study	Problem	Original	Dropped	Final
CT-94	Unusable Data (1) & Protocol Violation (1)	16	2	14
CT-97	Protocol Violation (1)	7	1	6
CT-99	Unusable Velocity data (4) [only removed from Subrange analysis]	12	0	12
Total		35	3	32

Analysis of Hypothesis 1: Subranges of ISI

This hypothesis states, “People use a different tapping strategy for fast rates (short ISIs) than they do when tapping at slow rates (long ISIs).” For the purpose of analysis, this proposition will be stated as the null hypothesis—that there will be no indication of subranges across ISI level—for each of the three applicable data sets. The two variables to be analyzed are Duty Cycle (DI/IRI) and MIDI Velocity values.

- H1_A_NULL: For the CT-94 data set, the changes in Duty Cycle values will be smooth (proportional) across ISI rates and there will be no indication of non-linear components.
- H1_B_NULL: For the CT-97 data set, the changes in Duty Cycle values will be smooth (proportional) across ISI rates and there will be no indication of non-linear components.
- H1_C_NULL: For the CT-99 data set, the changes in Velocity values will be smooth (proportional) across ISI rates and there will be no indication of non-linear components.

To address these questions, we must examine whether the function of the produced IRIs (or other measured variables) show discontinuities when plotted over the ISI range. If so, an additional post hoc goal is to determine the point along the ISI range that best corresponds to the hypothesized boundary between subranges.

In the Null models, DI values increase proportionately with the ISI rate increase, which in turn causes the Duty Cycle ratio to be constant. Such stationary data can be fully described with a single parameter, y-Intercept, and this function illustrates a null model in which no subranges can be detected. By comparing each subject's observed data to the stationary data model, one can gauge how well the former fits the latter. Similarly, the observed Velocity function has been fitted to its equivalent Null model.

In the CT-94 data set, each subject's series of 50 continuation taps provided 49 IRIs for analysis over an ISI range of 275ms-875ms. The tapping target for the finger was a fixed platform. The intervals were measured by interrupting a light beam and the index finger was constrained to be the only part of the hand that could move. The Duty Cycle ratio represents the length of the active pulse (DI) within the time allocation. Converting the DI and its associated IRI values to a ratio serves to normalize the data so that appropriate comparisons can be made for differing ISI target rates.

Figure 4 presents subject averages for the CT-94 data set. The average Duty Cycle ratio values calculated for each of these fourteen subjects is plotted across the ISI range. Then these individual averages are themselves averaged together to form

a Grand Average Duty Cycle ratio. Note the variability in DC ratio values produced by the different subjects.

In Figure 5, the CT-94 Duty Cycle Grand Average (from Figure 4) is compared to a Null model in which the DI interval increases proportionally across the entire ISI range. This Null Model was calculated as a function that can be described with a single parameter, expected value, that is based on the observed DC values. The assumption that the DI (Down Interval) should increase proportionally across ISI is a reasonable and parsimonious prediction, given that the overall IRI (Interresponse Interval) is known to increase at an approximately proportionate rate across that same range.

From Figure 5, it is visually evident that the Duty Cycle Average curve is unlike the Null model curve, in that a single parameter does not describe its behavior well. To quantify this distinction, a Trend Analysis was performed on these Duty Cycle observations. An SPSS for Windows GLM Repeated Measures Within Subjects Contrasts analysis revealed a linear trend ($F(1,13) = 11.33, p < .005$), which permits us to reject the Null hypothesis.

However, the Duty Cycle Average curve in Figure 5 is also unlike the sharply discontinuous step function that would indicate a distinct transition point between two subranges. Instead the curve of the Duty Cycle ratio overall average function decreases in a smooth fashion across the ISI domain from about 37% at ISI=275ms to about 23% at ISI=875ms.

In the CT-97 data set, each of the six subjects' series of 28 continuation taps provided 27 IRIs for analysis over an ISI range of 275ms-975ms. The tapping target

was the surface of a pushbutton keypad on a commercial MIDI drum machine and the intervals were measured as MIDI music events.

Figure 6 shows the subject Duty Cycle averages for the CT-97 data set. This graph is analogous to the averages plotted in Figure 4. This graph represents the Duty Cycle ratio averages across their entire ISI range of 275ms to 975ms—two more ISI rates than those presented in the CT-94 study. Note that the DC ratio subject averages show very little dispersion, especially as compared to Figure 4.

Figure 7 is a comparison of the Duty Cycle Grand Average with a Null Model composed of the expected value for the CT-97 data set. As with Figure 5, it is visually evident that the Duty Cycle Grand Average curve is unlike the Null model curve. An SPSS Trend Analysis on these Duty Cycle data revealed a strong linear trend ($F(1,5) = 1368.57, p < .0001$), a quadratic trend ($F(1,5) = 237.27, p < .0001$), and a cubic trend ($F(1,5) = 31.46, p < .002$). These significant trends permit us to reject the Null hypothesis.

However, Figure 7 clearly does not support the notion of a sharp step function discontinuity in Duty Cycle; in fact, the smoothness of the decline from about 16% at ISI=275ms to about 4% at ISI=975ms is the most salient feature of the Duty Cycle Average for the CT-97 data.

In the CT 99 study, the Velocity variable was introduced as an alternate means to help to determine if subranges could be discerned within the overall ISI range. In the CT-99 data set, each of the subject's series of 28 continuation taps provided 27 IRIs for analysis over an extended ISI range: 275-975, 1600, 1800 & 2000ms. The target was a dense rubber keypad on a commercial MIDI drum

machine. According to the MIDI standard, the Velocity parameter ranges from 0 (silent) to 127 (loudest produced sound). The drum machine's touch-sensitive keys are calibrated to divide this range into eight subgroups, so the captured Velocity keystrokes can take on one of these Velocity values: 15, 31, 47, 63, 79, 95, 111, & 127. For analytic simplicity, these ordinal Velocity values were converted to equivalent values (1-8). No subject tapped the target keypad at the highest Velocity value in any of the trials, so the Y-axis for all Velocity graphs was reduced to range from 1 to 7.

In Figure 8, the average subject MIDI Velocity values for the CT-99 data set are displayed for the subjects represented in this graph, over the 15 sub-second ISIs (275ms-975ms). Note that the Subject Velocity Grand Average has a positive slope, which indicates that the participants were tapping the keypad harder at the longer intervals.

This distinction can be seen more readily in Figure 9, in which the observed Average Velocity curve is compared to its Null Model curve for the sub-second ISI levels. An SPSS Trend Analysis of the CT-99 Velocity data showed a definite linear trend ($F(1,10) = 15.88, p < .003$), which again permits us to reject the Null hypothesis.

As with the Duty Cycle analyses for CT-94 and CT-97, this observation points to a smooth change rather than a sharply discontinuous change in Velocity values over this ISI range.

Figure 10 recapitulates Figure 8, except that it includes the three slowest ISI levels (1600ms, 1800ms, & 2000ms).

Figure 11 rearranges the Velocity data seen in Figure 10, into a Box and Whisker plot by ISI level, so that the dispersion of the Velocity variable by ISI level can be readily comprehended. This was done because the Velocity values associated with the slowest ISI levels (1600ms, 1800ms, & 2000ms) are plotted as individual data points on the right side of the graph, and it is somewhat difficult to visually determine the variability of these slowest levels from Figure 10 alone. Figure 11 presents the average MIDI Velocity values for the entire CT-99 data set as a Box and Whisker graph, by ISI levels. Figure 11 shows that the range of Velocity values is typically between about 2.75 to about 3.00, except at the fastest and the slowest ISI levels, where the range increases. The Interquartile Range (IQR), indicated by the area within each rectangle, does not appear to show systematic change over ISI level.

Figure 12 recapitulates Figure 9, except that it also includes the three slower ISI levels. The positive trend of the Grand Average curve, seen in Figure 9, is less pronounced when the additional three data points are considered; however, this apparent ‘asymptote’ may well be an artifact of the limited Velocity range provided by the MIDI drum machine used to measure the tapping data.

From these data, it is apparent that Duty Cycle and Velocity change over the ISI range; however, there is no clear evidence that these variables change discontinuously or abruptly, and therefore there is no evidence for discrete subranges.

Analysis of Hypothesis 2: Instrumental Drift and Correction

This hypothesis states, “People use a targeting strategy for regulating produced IRIs by introducing a small negative bias (drift) into trial tapping. This negative bias is

then countered by positive corrections.” To test this hypothesis, it must be divided into its two measurable components: Drift measured as Robust Resistant Line Slope, and Correction measured in terms of IRI First Differences. Evidence for the Drift hypothesis would consist of finding systematic drift throughout trial tapping data. Evidence for the Correction hypothesis would consist of observable bimodal distributions in IRI First Difference data.

For the purpose of analysis, these experimental hypotheses will be stated in the Null manner—that changes in Robust Resistant Line Slope and IRI First Differences are random noise—for each of the three applicable data sets.

- $H2_{A_NULL}$: For the CT-94 data set, the Robust Resistant Line slope values for trial IRIs will not show significant trend across ISI rates.
- $H2_{B_NULL}$: For the CT-97 data set, the Robust Resistant Line slope values for trial IRIs will not show significant trend across ISI rates.
- $H2_{C_NULL}$: For the CT-99 data set, the Robust Resistant Line slope values for trial IRIs will not show significant trend across ISI rates.
- $H2_{D_NULL}$: For the CT-94 data set, the positive and negative First Difference values for trial IRIs will not show significant differences in distribution symmetry across ISI rates.
- $H2_{E_NULL}$: For the CT-97 data set, the positive and negative First Difference values for trial IRIs will not show significant differences in distribution symmetry across ISI rates.

- $H2_{F_{NULL}}$: For the CT-99 data set, the positive and negative First Difference values for trial IRIs will not show significant differences in distribution symmetry across ISI rates.

Drift

To address the first experimental hypothesis, Robust Resistant Line slope values for trial IRIs will not show significant trend across ISI rates for the CT-94 data set, see Figures 13 and 14. These two graphs plot average trial slopes for each subject across the 13 ISI levels (275ms-875ms) available for this data set. Figure 13 shows each subject's average as well as a slope Grand Average of all subjects; most of the subject average slopes show negative slopes, and the Grand Average slope decreases in magnitude over ISI range. Figure 14 compares the Robust Resistant Line Slope Grand Average to the single-parameter Null Model (expected value = -0.19). A visual inspection of this graph allows us to conclude that these curves are both quantitatively and qualitatively different

The second experimental hypothesis states that the Robust Resistant Line slope values for trial IRIs will not show significant trend across ISI rates for the CT-97 data set. For a visual representation of these slopes, both individual averages and group average, see Figures 15 and 16. These two graphs plot subject's trial Robust Resistant Line slopes across the 15 ISI levels (275ms-975ms) from the CT-97 data set. Figure 15 shows each subject's individual average, as well as the Robust Resistant Line Slope Grand Average; like Figure 13, the average slope value is also negative. Figure 16 compares the Robust Resistant Line Slope Grand Average to the single-parameter Null

Model ($y\text{-Int} = -0.10$). As with the earlier comparison in Figure 14, these curves are quite different.

The third experimental hypothesis states that the Robust Resistant Line slope values for trial IRIs will not show significant trend across ISI rates for the CT-99 data set. See Figures 17 and 18 for the respective Robust Resistant Line slopes—individual and group averages. These two graphs plot subject's trial Robust Resistant Line slopes across all 18 ISI levels (275ms-975ms, 1600ms, 1800ms, & 2000ms) presented in the CT-99 data set. Figure 17 shows each subject's individual average, as well as an Robust Resistant Line Slope Grand Average for all subjects—note that an effort was made to maintain the scale of the X-axis, which explains the amount of white space on the right-hand side of this graph. Figure 18 compares the Robust Resistant Line Slope Grand Average to the single-parameter Null Model ($y\text{-Int} = -0.25$).

Correction

The three Correction hypotheses state that for their respective data sets, “Positive and negative First Difference values for trial IRIs will not show significant differences in distribution symmetry across ISI rates.” Essentially, the expectation for this hypothesis is that if there is evidence for an ongoing Drift and Correction process, then the differences between successive IRIs, both positive and negative, would form a bimodal distribution, presumably with fewer-but-larger positive values and more-but-smaller negative values.

The Drift/Correction hypothesis predicts that the effects of Elastic Tapping would predominate at the faster ISI levels, so the probability of discerning a Correction mechanism would be greatest at the longest (Intermittent Tapping) ISI levels.

Accordingly, histograms were constructed for the slowest ISI levels common to all three data sets (775ms, 825ms, and 875ms), for all subjects.

There are no reliable computational methods for restoring a mixture of multiple distributions, whose characteristics are not known, into their constituent distributions (C.E. Collyer, personal communication, May, 2000). Therefore, the method chosen to detect the presence of bimodality was visual inspection of histograms. Because this is a pattern-recognition process rather than a statistical procedure, the criteria used in this study to assess bimodality will be addressed. To illustrate this assessment process, a series of histograms (Figure 19a-Figure 19g) were created for this manuscript. These model distributions were compiled as random variables, using the SPSS for Windows Transform/Compute RV .NORMAL () function. From these distributions, histograms were created with the SPSS for Windows Graph/Histogram facility. Note that the Figure 19 distributions are intended to be explicatory, rather than exactly modeling IRI First Distribution data, and for simplicity these distributions contain no negative numbers and are less variable than actual IRI First Difference data.

Figure 19a is a histogram that depicts an idealized bimodal distribution ($n=240$, $\text{mean}=50$, $\text{sd}=20$), which is actually two mutually-independent distributions that have been pooled. The values of this bimodal distribution will be replaced, in step-wise fashion, by values sampled from the normal (randomly derived) distribution ($n=240$, $\text{mean}=50$, $\text{sd}=9.9$) shown in Figure 19b. In these histograms, a normal curve has been superimposed over the plotted distribution.

Figure 19c shows the shape of the mixed distribution that consists of 80 low values, 80 high values, and 80 normal values (2/3 bimodal and 1/3 normal). Though there are

intermediate data points in this histogram, its bimodal origins are quite pronounced. Figure 19d is a mixed distribution that consists of 60 low values, 60 high values, and 120 normal values (1/2 bimodal and 1/2 normal). This multi-modal distribution still reveals signs of bimodality. If any of the IRI First Difference distributions were shaped like Figure 19c or Figure 19d, they would be judged as showing evidence of bimodality.

Figure 19e is a mixed distribution that consists of 40 low values, 40 high values, and 160 normal values (1/3 bimodal and 2/3 normal). This distribution would be judged as possibly evidential of bimodality.

Figure 19f is a mixed distribution that consists of 30 low values, 30 high values, and 180 normal values (1/4 bimodal and 3/4 normal). This distribution would be judged as not inconsistent with bimodality, but too ambiguous to be so classified.

Figure 19g is a mixed distribution that consists of 20 low values, 20 high values, and 200 normal values (1/6 bimodal and 5/6 normal). At best, its shape would be judged ambiguous in terms of possible bimodality.

For the CT-94 data set, the 42 IRI First Difference histograms (14 subjects by three ISI levels) showed no tendency towards being bimodal. Instead, the shapes of these histograms were primarily unimodal, and none even approached the “possibly bimodal” appearance of Figure 19f. Figure 20 shows a representative CT-94 histogram that plots the 236 data points for Subject A02 at ISI=825ms.

For the CT-97 data set, the 18 IRI First Difference histograms (six subjects by three ISI levels) likewise showed no clear indications of bimodality, and were for the

most part unimodal. Figure 21 shows a representative CT-97 histogram that plots the 78 data points for Subject B08 at ISI=825ms.

Similarly for the CT-99 data set, the 36 IRI First Difference histograms (12 subjects by three ISI levels) showed no unambiguous signs of bimodalality. Figure 22 shows a typical histogram for the CT-99 data set, in this case the 52 data points for Subject C01 at ISI=825ms. These data support the conjecture that negative Drift is present for most trial IRI data; however, there is no evidence for Correction.

Chapter 5: Discussion

This study investigated continuation tapping, which is a research window on human timing. Continuation tapping is the simple task of copying an audible steady rhythm by tapping along with one's finger, and then continuing the tapping process after the audible tones are withdrawn. Specifically, this study attempted to learn more about the means by which a person can maintain an arbitrarily-selected tempo or rate of tapping. The study was divided into two sections.

The first aim of this study was to determine whether two tempo subranges of tapping behaviors exist, and whether subjects used different tapping strategies for each subrange as reported in Vaughan, Matson, & Rosenbaum (1998). Two different variables were analyzed for the subrange/tapping style phase of the study: Duty Cycle (normalized time-on-target) and Velocity (collision impulse on target).

The Duty Cycle data from the first two data sets (CT-94 and CT-97) and the Velocity data from the CT-99 data set showed smooth curves as they changed across the ISI domain. These variables did not show any abrupt discontinuity that would differentiate distinct subranges for continuation tapping in the sub-second ISI domain, and therefore this study did not support the first hypothesis that Duty Cycle and Velocity data can distinguish such subranges.

Although the CT-94 and CT-97 Duty Cycle curves changed gradually as a function of ISI, they did not do so in an identical fashion. The characteristics of the DC curves for these data sets differed in two major aspects. First, the CT-94 Duty Cycle averages were larger than those for CT-97. Second, the CT-94 Duty Cycle averages were more variable than their CT-97 counterparts.

The differences in magnitude are thought to be an artifact of the instrumentation used to measure subject tapping behavior in their respective studies. Specifically, the CT-97 apparatus used a pushbutton switch (normally open) to measure the "finger-down" and the "finger-up" events which comprise an individual finger tap. This precise demarcation of target contact stands in contrast to the technique used for the CT-94 data set, which measured these events when the subject's fingertip interrupted a beam of light. The infrared lightbeam was above the target's surface and was positioned parallel to its plane, so the light beam was actually broken prior to the instant that the fingertip touched the surface. Furthermore, the lightbeam continued to be interrupted for some period of time after the fingertip was lifted from the target surface. These additional periods, which will be termed "travel time", would be included in the measurements, which would increase the DI values; inflated DI values would, in turn, increase Duty Cycle values.

The differences in variability between the CT-94 and CT-97 Duty Cycle curves are thought to originate from two sources. The first possible source of variability could be that variations in the trajectory of the fingertip to the target could disproportionately amplify the variability of "travel time" incurred while tapping on the CT-94 target. The second possible source of variability is that the target for the CT-97 apparatus was a spring-loaded pushbutton that would have provided a counterpoise to the muscle impulse that initiated the tap, as well as kinesthetic feedback when the normally-open switch was closed. Such cues could have helped delimit the DI and thus make it more punctate and less variable for the CT-97 data set. By contrast, the target for the CT-94 was fixed and inelastic, so no equivalent regulatory support was available.

The particular smoothness of the CT-97 Duty Cycle curves is accounted for by noting that as target ISI increases, Down Interval values remain relatively constant (or increase slowly). When the numerator (DI) is fairly stable, and the denominator (IRI) increases at a steady 50ms increase for each target ISI level, then the DC ratio will necessarily decrease proportionately. Therefore, the assumption that both the active (DI) and passive (UI) components of the IRI increase proportionately across target ISI levels must be replaced with an alternative explanation that better describes the observed data.

The most parsimonious explanation of this phenomenon is that essential timing calculations take place during the UI fraction of the total IRI, rather than being distributed proportionally between the two fractions. Since the DI fraction appears to have relatively little to do with overall timing regulation, it may take on the role of a motor event that approximates, but is not exactly, a temporally constant value.

In the CT-99 data, MIDI Velocity values were examined instead of DC ratios for evidence of discrete subranges. These Velocity values increased across the ISI range until about the 775-825ms levels, whereupon average Velocity values stabilized within a narrow range (± 0.2) throughout the remainder of the ISI domain (875-2000ms). This probable "ceiling effect" was most likely brought about by the instrumentation's restricted range and limited sensitivity for measuring finger-tap impulses (see Limitations of Study section). In any case, this Velocity curve showed no sign of the step function that would be predicted at the boundary between two discrete subranges.

In short, neither the DC ratio data nor the Velocity data provided evidence of discrete subranges across the ISI target range. This conclusion expands upon the differences in tapping behavior observed by Vaughan et al (1998). The apparently qualitative distinction between tapping behavior at 333ms and at 2000ms was so sharp that terming one "elastic" and the other "intermittent" was reasonable. The current study would revise this account by suggesting that the subrange hypothesis resulted from sparse sampling --that is, samples obtained from a distribution's "tails." When intermediate IRI values are measured, DC and Velocity values are observed to change continuously as a function of ISI.

The second aim of the study was to determine whether the subjects used a "target-sweeping" strategy to regulate their IRI production. In this proposed strategy, they would introduce continual, small negative biases ("drift") which would then be countered by occasional, larger positive corrections. If this regulatory method were used to maintain an average rhythm, there would be evidence of bimodal symmetry in the distributions of the IRI First Differences. This "correction" hypothesis was not supported by these data.

This study confirmed the presence of negative drift for all three data sets over most of the ISI domain (excluding the 775-875ms ISI region for the CT-97 and CT-99 data sets). However, Drift is only one of the two conditions of this hypothesized dual process. The inspection of the distributions of IRI First Differences across all three data sets showed no indication of Correction, defined as systematic bimodal distributions at the three longest common ISI levels (775ms, 825ms, and 875ms).

Context

Previous studies of human timing and tapping have uncovered a number of tempo-dependent phenomena, such as the finding that most subjects' average tapping is within about 3% (+/-) of the target ISI value, and that most subjects are unable to accurately reproduce rates much faster than four taps per second (Collyer et al, 1992; Collyer et al, 1994). Collyer and Church (1998) found and reproduced the Oscillator Signature, which indicates a systematic error in reproducing sub-second Interstimulus intervals.

The current study provided support for those earlier findings, and added a link between Collyer's work and that of Vaughan et al (1998). Specifically, this study helped to confirm the Vaughan findings that both collision impulse (Velocity) and dwell time (DC ratio) are appreciably different at the ISI target range extremes; however, this study did not confirm the presence of distinct categorical subranges. It did however confirm the presence of negative drift over trial IRIs.

Limitations of Study

The primary limitations of this study were related to problems inherent in combining multiple data sets for analysis; specifically, using two archival data sets (CT-94 & CT-97), in conjunction with a new data set (CT-99) collected solely for this study. Although the CT-94 and CT-97 studies focused on continuation tapping behavior, each earlier study used a different protocol, a different apparatus, and a different experimental setting from those used in the CT-99 data set. These differences mean that comparisons of measured tapping behavior among these data sets must be made with some caution, while remaining aware of possible confounds that could have

been introduced by differences between the studies such as trial length (e.g., 50-tap vs. 28-tap).

A design decision for the CT-99 data collection that may have been problematical was to limit each participant to two sessions of continuation tapping at all target ISI levels. The rationale behind this two-session preference was to decrease the subjects' burden of scheduling more than two sessions. The major problem with this decision is the hazard of missing data; for example if a given trial is missing, then averages are not calculable.

Another design decision that affected the CT-99 data set was using an apparatus that could not simultaneously measure both target impulse and finger-up/down values. Because these latter data were unavailable, Duty Cycle ratios could not be calculated, and thus comparisons could not be made across all three data sets.

A final concern that should be acknowledged is the question of limitations to generalizability. Beyond such obvious issues as selecting a sample that is representative of the general population, this turns out to be a difficult question to answer. There are two reasons that this question is so problematical for continuation tapping. First, people are good at this task and so there is a restricted range of performance that can be studied. Second, individual differences may be so salient to CT performance that averaging measured variables across subjects can mask rather than reveal information (see Figures 4, 8, 13, 15, and 17).

Suggestions for Future Research

One possible response to the concerns regarding generalizability is to reframe the goal of continuation tapping research away from a strictly normative approach

(attempting to discover general axioms that apply to larger populations), and towards an individual differences approach. From the latter perspective, a researcher would measure and analyze continuation tapping behavior longitudinally by subject, rather than across subjects. Such CT data (e.g., Oscillator Signature or Drift) would be considered to be aspects of a multidimensional temporal profile that could be employed, for example, in neurological assessment.

Continuing the theme of individuals differences, one recommendation for further research is to explore how background variables—such as time perception or reaction time—modulate a subject's continuation tapping performance. Another interesting research area would involve systematically manipulating additional independent variables, for example, the degree of target elasticity or the extent of target travel, to determine their effect on variability of task performance.

Figure 1: Oscillator Signatures—CT-94,.CT-97, & CT-99 Data Sets

Figure 2: CT-99 Apparatus Diagram

Figure 3: Cakewalk MIDI Sequencer Screenshot

Figure 4: Subranges, CT-94 Duty Cycle, Subjects' Averages and Grand Average

Figure 5: Subranges, CT-94 Duty Cycle Grand Average vs. Null Model

Figure 6: Subranges, CT-97 Duty Cycle, Subjects' Averages

Figure 7: Subranges, CT-97 Duty Cycle Grand Average vs. Null Model

Figure 8: Subranges, CT-99 Velocity, Subject's Averages/Grand Average (fast ISIs)

Figure 9: Subranges, CT-99 Velocity Grand Average vs. Null Model (fast ISIs)

Figure 10: Subranges, CT-99 Velocity, Subjects' Averages/Grand Average (all ISIs)

Figure 11: Subranges, CT-99 Velocity Box and Whisker Plot (all ISIs)

SUBRANGES: CT-99 Velocity of Subject Velocity Values by ISI Levels

Figure 12: Subranges, CT-99 Velocity Grand Average vs. Null Model (all ISIs)

Figure13: Drift/Slope CT-94, Subjects' Averages and Grand Average

Figure 14: Drift/Slope CT-94, Grand Average

Figure 15: Drift/Slope CT-97, Subjects' Averages and Grand Average

Figure 16: Drift/Slope CT-97, Grand Average

Figure 17: Drift/Slope CT-99, Subjects' Averages and Grand Average (all ISIs)

Figure 18: Drift/Slope CT-99, Grand Average (all ISIs)

**DRIFT: CT-99 Robust Resistant Slope Grand Average
and Null Model (Expected Value) for all Subjects**

Figure 19a: First Difference Example: Bimodal Distribution

Figure 19b: First Difference Example: Normal Distribution

Figure 19c: First Difference Example: 2/3 Bimodal and 1/3 Normal Distributions

Figure 19d: First Difference Example: 1/2 Bimodal and 1/2 Normal Distributions

Figure 19e: First Difference Example: 1/3 Bimodal and 2/3 Normal Distributions

Figure 19f: First Difference Example: 1/4 Bimodal and 3/4 Normal Distributions

Figure 19g: First Difference Example: 1/6 Bimodal and 5/6 Normal Distributions

Figure20: First Difference Histogram, CT-94, Subject A09 (ISI=825ms)

Figure21: First Difference Histogram, CT-97, Subject B06 (ISI=825ms)

Figure22: First Difference Histogram, CT-99, Subject C01 (ISI=825ms)

Appendix A: Research Protocol

[*Session 1 only*: “Thank you for volunteering to participate. Before we get started, please read this consent form. If you agree to its terms, please sign both copies and then keep one copy.” ➔present two copies of Consent Form; log Sname & Snum←]

“This study is being done to learn more about how people maintain rhythms – in this case, by tapping their finger. I’d like you to listen to some clicking sounds, like a metronome, and then have you tap along with those sounds on this drum machine.”

➔show Alesis SR16 & point out target keypad←

“There will be about 20 different tempos that you will tap along with in each session, and I need two sessions from each participant, at least one day apart. We’ll follow the same procedure for each tempo:”

1. “First, you will listen to the sounds without tapping.
2. Next, I’ll play the sounds again, and as you listen to the rhythm, you will tap the keypad ‘in synch’ with the sounds. As the sounds fade out, please keep tapping until you hear the cymbals sound; then you can stop tapping.
3. Then, we will move on to a different tempo, and so on until we do all the scheduled tempos.”

“Before you actually start tapping, I’d like to give you a demo of the tapping process.”

➔demonstrate CT on Cakewalk w/ speakers, using practice ISIs 333ms or 1400ms←

“Notice how I’m holding my arm flat and tapping with my wrist & hand, so that the taps sound very distinct – please try to keep your tapping sounds distinct. Feel free to adjust the position of your chair or the position of the drum machine – whatever is most comfortable.”

“OK, it’s your turn to practice. Remember, if you ‘stumble’ or miss a tap, don’t worry about it--just keep going. Also, let’s switch from the speakers to your headphones.”

➔give headphones & run Cakewalk practice session w/ ISIs 333ms & 1400ms←

➔check for adequate Vel levels. If too low, demo & ask for ‘sharper tap’; if OK, check label of Snum floppy for assigned sequence letter & proceed in that order←

Appendix B: CT-99 Consent Form

The University of Rhode Island
Department of Psychology, Kingston, RI 02881

Continuation Finger Tapping study CONSENT FORM for Research (You will receive a copy of this consent form.)

You have been asked to take part in the research project described below. The researcher, Arthur Little, will explain the project to you in detail. Feel free to ask him any questions about this study during your two sessions. If you have questions later, Art can be reached at 401-792-3648.

To participate in this study, 1) you must be at least 18 years old, and 2) you must not have any medical/orthopedic problems with your fingers, hands or wrists (e.g., tingling or numb fingers).

Purpose: This study seeks to learn more about how people synchronize to, and maintain finger tapping at a steady target rate. Knowledge of how people regulate constant tempos may provide information on how our brains measure and use short time intervals.

Procedure: There will be two sessions held on different days. Each session will consist of tapping your finger to a clicking sound at a specific tempo. Once you have had time to synchronize your tapping with the clicks, the sounds will stop and you will continue to tap and maintain that tempo until signaled to stop. There are 18 target tempos (fast and slow) per session, and each session should take less than 25 minutes.

Risks: There are no known risks to the continuation tapping procedure. The continuation tapping task is one of the oldest experimental methods used in perceptual and physiological psychology. The medical restriction in the 2nd paragraph above is only a safety precaution.

Benefits: Although there is no direct benefit to you for taking part in this study, you should know that through your efforts, the researcher may learn more about human timing regulation.

Confidentiality: Your part in this study is confidential. All of your recorded responses will be assigned an anonymous ID number, which is the only way your data will be identified. All computer files will be password protected by the researcher, and all hardcopy files/magnetic disks will be locked in filing cabinets.

Your Participation: You do not have to take part in this study—that decision is up to you. If you do decide to take part in this study, you may change your mind and quit at any time. Whatever you decide will not penalize you in any way. If you wish to quit, simply inform Art of your decision.

Rights & Complaints: If you are not satisfied with the way this study is conducted, you may discuss your complaints with Art Little or anonymously with Dr. Charles Collyer, Chair, Psychology Dept.

You have read this Consent Form. Your questions have been answered. Your signature on this form means that you understand this information and that you agree to participate in this study.

_____/____/____	_____/____/____
Signature of Participant Date	Signature of Researcher Date

_____	_____
Printed/typed Name	Printed/typed Name

Appendix C: Randomized Sequences for ISI Presentation

Sequence A	Sequence B	Sequence C	Sequence D
Practice	Practice	Practice	Practice
333	1400	333	1400
1400	333	1400	333
Block 1	Block 1	Block 1	Block 1
375	875	475	525
675	525	775	625
325	675	975	325
775	725	725	975
825	925	675	475
2000	1800	1600	1800
Block 2	Block 2	Block 2	Block 2
425	575	525	575
975	625	925	425
525	325	375	725
275	275	825	925
925	475	325	675
1800	2000	2000	1600
Block 3	Block 3	Block 3	Block 3
475	825	575	875
575	425	875	825
875	975	275	275
725	375	625	375
625	775	425	775
1600	1600	1800	2000

Appendix D: Listings

Listing 1: Representative CT-94 data file: ISI=325ms. (abridged)

```
; Name:      {subject name}
; date       {date & time}
; Debounce delay75 ms
; Trials/Session: 5
; Beep: 50msec on, 275msec off
; N1=50 N2=50
; T1=75 T2=75
; End of Header

; Trial 1
; Synchronization Begins Here
S      0
S      325
D      375
U      513
S      650
D      719
U      810
S      975
D      1006
U      1116
S      1300
.
.
.
D      16580
U      16678
; Continuation Begins Here
D      17237
U      17328
D      17568
U      17645
D      17891
U      17973
D      18191
U      18285
.
.
.
```

Listing 2: MF2T Output for CT-99 MIDI Data File: ISI=275ms. (abridged)

```
MFile 0 1 480
MTrk
0 Meta SeqName "275ms, CT99"
0 Meta SeqName "Subj = 07"
0 Meta Text "aal_exper "
0 Meta Text "Sess = 1"
0 SMPTE 96 0 3 0 0
0 TimeSig 4/4 24 8
0 KeySig 0 major
0 Tempo 275002
On ch=10 n=36 v=64 56
On ch=10 n=36 v=0 480
On ch=10 n=36 v=64 536
On ch=10 n=36 v=0 556
On ch=10 n=47 v=15 556
On ch=10 n=47 v=0 960
On ch=10 n=36 v=64 971
On ch=10 n=47 v=15 973
On ch=10 n=47 v=0 1016
On ch=10 n=36 v=0 1428
On ch=10 n=47 v=15 1428
On ch=10 n=47 v=0 1440
On ch=10 n=36 v=64 1496
On ch=10 n=36 v=0 1910
.
.
.
On ch=10 n=47 v=79 20358
On ch=10 n=47 v=0 20358
Meta TrkEnd
TrkEnd
```

Listing 3: QuickBasic Extraction/Conversion Program (IRI/DI/UI/Vel)

```
'22aug99, ver G: Do 2 sessions @ once; extreme val def now (<360
' & >600); option to save either data file or verbose data file
,
'19aug99, ver E/F: Added output last timestring$ w/ IRI value &
' expected vals to locate bounce; outlier < & > symbols; cleanup
,
'15aug99, ver D: Added add'l automation
,
'10aug99, vers B/C: Added verbose output to locate home IRI for
' orphan ' bounce intervals; input vbl SubjNo$
,
' 8aug99, ver A: Proof-of-concept by AAL
'Data Extractor/Converter for CT-99 MF2T Output Text Files
'*****
DECLARE SUB LineParser (Flag!)
ON ERROR GOTO ErrWarning
DIM SHARED Lin$, VelVal$, IRI$, ISI%, Flag!, TmStmpFlg$
,
INPUT "Which Subject to process (eg, 03 or 10) "; SubjNo$
INPUT " Verbose Output (include timestamp info [Y/N]) ";
TmStmpFlg$
    TmStmpFlg$ = UCASE$(TmStmpFlg$)
,
FOR Sesn% = 1 TO 2 ' <== Outermost Loop Begin
    Sesn$ = LTRIM$(STR$(Sesn%)): SessNo$ = SubjNo$ + Sesn$
    Filnfo$ = "Filnf" + SessNo$ + ".LST"
    OPEN Filnfo$ FOR INPUT AS 1 ' List of .TXT files for a subject
        LINE INPUT #1, FileDir$ 'Get dir/pathname of these files
        LINE INPUT #1, SubjSess$ 'Get 3-char$ (eg 071 = Subj7, Sess1)
        IF SubjSess$ <> SessNo$ THEN PRINT "Session Mismatch":STOP
        ' Safety check halt
        IF TmStmpFlg$ = "Y" THEN
            SufxOutfil$ = "99.DVT" 'Verbose Data mode
        ELSE
            SufxOutfil$ = "99.DAT" 'Normal Data mode
        END IF
        DATAFIL$ = "CUM" + SubjSess$ + SufxOutfil$
        OutFile$ = "F:\ALD_TO~1\" + DATAFIL$
        ,
        OPEN OutFile$ FOR APPEND AS #3 'Cumulative data file out
        ,
DO 'Main outer loop process all txt files (18 ISI x 2 sessions)
    LINE INPUT #1, InFile$
    OPEN FileDir$ + "\" + InFile$ FOR INPUT AS 2'Data filename
    DO UNTIL LEFT$(Lin$, 6) = "0 Meta" 'Gets ISI level
        LINE INPUT #2, Lin$
    LOOP 'Finds line that contains the target ISI level
    ISI$ = MID$(Lin$, 17, 4): ISI% = VAL(ISI$)'Extracts$=>tonum
```

```

PRINT #3, "ISI="; ISI$ 'Write filename/tempo B4 IRI datalist
'PRINT #3, " IRI"; CHR$(9); " Vel"'Write header 4 IRI datalist
DO UNTIL INSTR(Lin$, "n=49") 'Until eof cymbal sound
  LINE INPUT #2, Lin$
  IF LEFT$(Lin$, 4) = "5336" THEN PRINT #3, "00"CT begins
  IF INSTR(Lin$, "n=47") THEN
    CALL LineParser(Flag!)
  END IF
LOOP 'Process-a-text-file inner loop
CLOSE #2
Lin$ = "": IRI$ = "": VelVal$ = "": NewTmStmp$ = ""
OldTimeStamp$ = "": AbsTimeStamp$ = "": IRI% = 0: Flag! = 1
' CleanUp for next txt file
LOOP UNTIL EOF(1) 'Process all 1 sessions's text files loop
CLOSE
NEXT Sesn% '<== Outermost Loop End--Does Both Subject's
Sessions
CLOSE 'Everything for this Subject
END
'*****ErrHndler*****
ErrWarning:
PRINT "Error "; ERR; " on line "; ERL
  SELECT CASE ERR
    CASE 3
      PRINT "Error #"; ERR
    END
    CASE 6
      PRINT "Overflow Error; ending program"
    END
    CASE 53
      PRINT "File Not Found:are files in subdirs?; end program."
    END
    CASE 55
      INPUT "File Already Open: If OK, enter y"; Retry$
      IF Retry$ = "y" THEN RESUME NEXT
    END
    CASE 64
      PRINT "Bad File Name; ending program."
    END
    CASE ELSE
      PRINT "Unexpected error."
    END
  END SELECT
END SELECT
SUB LineParser (Flag!) STATIC
  IF Flag! = 1 THEN OldTimeStamp$ = "": Flag! = 0
  Vel$ = RIGHT$(Lin$, 2)
  SELECT CASE Vel$ '1-8 vals substituted for SR-16 MIDI vals.
    CASE IS = "=0" ' MIDI note Off val
      EXIT SUB ' Return to calling prog

```

```

CASE IS = "15"
  VelVal$ = "1"
CASE IS = "31"
  VelVal$ = "2"
CASE IS = "47"
  VelVal$ = "3"
CASE IS = "63"
  VelVal$ = "4"
CASE IS = "79"
  VelVal$ = "5"
CASE IS = "95"
  VelVal$ = "6"
CASE IS = "11" ' actually 111
  VelVal$ = "7"
CASE IS = "27" ' actually 127
  VelVal$ = "8"
END SELECT
NewTmStmp$ = LEFT$(Lin$, INSTR(1, Lin$, " "))
AbsTimeStamp% = VAL(NewTmStmp$) - VAL(OldTimeStamp$)
ExpTmStmp% = VAL(OldTimeStamp$) + 480
ExpTStmp$ = LTRIM$(STR$(ExpTmStmp%))
IRI% = AbsTimeStamp% * (ISI% / 480): IRI$ = LTRIM$(STR$(IRI%))
SELECT CASE AbsTimeStamp%
CASE IS < 360 'Flag Key Bounce event
SuIRI$ = "-" + IRI$ + "TSobs:" + NewTmStmp$ + "TSexp:" + ExpTStmp$
CASE IS > 600 'Flag Missed Tap event
SuIRI$ = "+" + IRI$ + "TSobs:" + NewTmStmp$ + "TSexp:" + ExpTStmp$
CASE ELSE
SuIRI$ = " " + IRI$ + "TSobs:" + NewTmStmp$ + "TSexp:" + ExpTStmp$
END SELECT
IF TmStmpFlg$ = "Y" THEN
  PRINT #3, SuIRI$ + " " + VelVal$ 'Verbose obs/exp stamps mode
ELSE
  PRINT #3, IRI$ + " " + VelVal$ ' for checking on bounces
  PRINT #3, IRI$ + " " + VelVal$ 'Data Only (4 analysis)
END IF
OldTimeStamp$ = NewTmStmp$
END SUB

```


Listing 4: Microsoft Excel Visual Basic for Applications (VBA) Macro

```
' TukeyRRupdate Macro Copy/Paste/Format Values to
Worksheets
' last updated--10/21/99
Dim SheetNo, SheetNum$, Subj$, Path$, FilNam$, PathFilNam$
Subj$ = InputBox("Which Subject?")
Path$ = "H:\Z1Dat_Raw\94Dat-A\" & Subj$ & "\Orig\Cont\"
SheetNo = 275
'
Do While SheetNo < 925 ' Open all worksheet files for
subj
    SheetNum$ = LTrim(Str$(SheetNo))
    FilNam$ = Subj$ & SheetNum$ & ".xls"
    PathFilNam$ = Path$ & FilNam$
    Workbooks.Open PathFilNam$
    SheetNo = SheetNo + 50
Loop '
'
Workbooks.Open "H:\Z1Dat_Raw\94Dat-A\TukeyRRTmpl.xls"
Do While SheetNo > 275
    SheetNo = SheetNo - 50
    SheetNum$ = LTrim(Str$(SheetNo))
    FilNam$ = Subj$ & SheetNum$ & ".xls"
    Workbooks("TukeyRRTmpl.XLS").Activate
    Range("H15:H20").Select
    Selection.Copy
    '
    Workbooks(FilNam$).Activate
    Range("H15:H20").Select
    Selection.PasteSpecial Paste:=xlPasteFormulas
    Range("A1").Select
    ActiveWorkbook.Close (True)
Loop ' Loops thru all worksheets "275" to "875"
ActiveWorkbooks.Close (True)
End Sub
```

Glossary

Accuracy – The degree to which an observed/produced value reflects the standard value. In this study, the degree to which the observed IRI values emulate the target ISI value.

Attractor – Equilibrium state (point or region) into which dynamic systems tend to settle as they change states.

Collision Impulse – Measure of the relative force of a subject's tap on a touch-sensitive MIDI keyboard; operationalized as a MIDI Note Velocity value.

Continuation Tapping (CT) – The Continuation Tapping task is comprised of two components: 1) Synchronization, and 2) Continuation. In the synchronization phase, the subject's finger tapping matches frequency with a series of pacer tones that are presented at equal intervals (ISIs). In the continuation phase, the pacer tones are eliminated and the subject attempts to maintain that rate of finger tapping. Those intervals are recorded as the IRIs.

Correction – Change(s) in first difference ($X_t - X_{t-1}$) values for CT data that serve to counteract the overall trial drift.

Data Smoothing – Analytic approach used to remove noise from data in order to aid pattern recognition; also called a Digital Filter or Low Pass Filter. Data smoothing tools include such techniques as Robust Resistant Line, Least Squares Regression Line, Median Smooths, Moving Averages, etc.

Down Interval (DI) – The motor-active, “finger-making-contact” phase of an IRI, it is also called Dwell Interval.

Drift – Non-stationary data; a consistent tendency for continuation tapping data to be biased either negatively, too fast, or positively, too slow; defined by the overall slope of a fitted robust resistant line.

Duty Cycle – The amount of the available time interval (IRI) that is occupied by the active pulse interval, expressed as a percentage. In this study, duty cycle is defined as $DI / (DI+UI)$.

Festination – A tendency to increase the speed and decrease the range of a motor task.

First Difference – In time-series analysis, the difference in value between a given observation and the previous observation; $X_t - X_{t-1}$.

Hertz (Hz) – Frequency of tapping or other oscillating process per second; for the CT task, it is defined as $1000/ISI$. For example, an ISI of 250ms corresponds to 4.0 Hz.

Intercept – The point at which the linear trendline (or other graphed function) crosses the y-axis.

Interresponse Interval (IRI) – Time interval between periodic subject responses, measured from onset to onset; sum of DI and UI. IRI is the principal dependent variable measured in the CT task.

Interstimulus Interval (ISI) – Time interval between the metronome-like pacer tones as measured from onset to onset. The choice of ISI determines the rate at which the synchronizing tones are presented. ISI rate is the IV specified in the CT task.

Isochronous – Tones (or other serial activity) that recurs at equal intervals; metronome-like uniform durations.

Key Pressure – Operationally defined for the CT-99 data set as the value of the ordinal MIDI Velocity parameter (1-8).

Limit Cycle – An attractor characterized by successive system states that settle into a repeating series of points—for example, the orbit of a satellite. It is also called a Periodic Attractor.

MIDI (Musical Instrument Digital Interface) – Protocol for creating, storing and transmitting the commands to play electronic music files.

MIDI Sequencer – Software used to record MIDI music files; a “music editor.”

Negative-Going Zero Crossing – In an Oscillator Signature, the point at which the wavelike function moves from positive values through the midpoint to negative values. This location may represent a natural point attractor, because IRIs for ISI rates above and below seem to “move toward” that value.

Oscillator Signature – A recurring pattern of deviations from accuracy detected by plotting the S’s average IRI divided by its target ISI, over the range of ISIs. In previous studies, the average of several subject’s oscillator signatures has been a nonlinear “W”-shaped wavelike function.

Perturbation – A disturbance to a system’s current state, as for example, the effect of injecting energy to an object that was previously in a stable orbit.

Point Attractor – A simple attractor in which a dynamic system settles to a single “basin of attraction.” The Negative-Going Zero Crossing point may help locate such a point attractor.

Precision – The degree of dispersion associated with the IRI continuation responses. Conceptually, precision is related to reliability in the sense of low-variance measurement.

Robust Resistant Line – Linear first-smooth line plotted between the median values of the first third and last third of the data. Sometimes called Tukey Line. By using medians, the robust resistant line is much less influenced by extreme values than is the least-squares (OLS) regression line.

Semi-Interquartile Range (SIQR) – Measure of variability calculated from ranking observations; $(Q_3 - Q_1)/2$. Analogous and proportionate to standard deviation for normal distributions, the SIQR is more resistant to the distorting effects of outlier values for skewed distributions.

Session – This is the period in which the subject performs all the day's trials.

Slope – The amount of change in unit y per unit x : $([y_2 - y_1]/[x_2 - x_1])$; “Rise divided by run”. In this study, slope value is calculated for the robust resistant line in order to determine drift (rate and direction of change) during continuation tapping.

Trial – One complete instance of synchronization tapping followed by continuation tapping. All of the trials at all of the ISI levels constitute a day's session.

Trimmed Mean – An arithmetic mean calculated after removing n percent of the smallest and largest cases. It provides a robust estimate of central tendency.

Trend – Non-stationary data; in this study, a consistent inclination of CT trial data to be biased either negatively (too fast) or positively (too slow).

Up Interval (UI) – The task-inactive, “finger-back-and-waiting” phase of an IRI. Sometimes termed “Back Interval.”

Velocity – MIDI term for the value that describes how fast a key was struck, and how loud its note will sound.

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