Rhythmic constraints on stress timing in English

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Suggested running title: Rhythmic constraints on stress timing

Abstract

The failure to document isochronous interstress intervals in spoken English may be attributed to the unconstrained nature of most experimental tasks. Some experiments are described which probe the degree to which the relative durations of interstress intervals within a series of repeated phrases are independent. The experiments introduce a novel paradigm, 'speech cycling', for investigating temporal phenomena in speech. The data reveal the presence of strong rhythmic constraints on stress timing which have hitherto eluded experimenters. It is argued that these constraints are evidence for a task-specific dynamical system in which prominent events (stress beats) are constrained to occur at specific, predictable, phases of an enclosing cycle. The dynamical system is characterized by entrainment between metrical levels, a principle which underlies rhythmic coordination in activities such as locomotion.

1 Introduction

Numerous phoneticians have suggested that English speech tends to exhibit roughly equal inter-stress intervals (Jones, 1918; Pike, 1945; Abercrombie, 1967). The first instrumental search for isochrony in English was carried out by Classé (1939). Using the recently developed kymograph, he measured the intervals between the onsets of nuclear vowels of stressed syllables. Strict isochrony was only observable when the rhythmic groups had similar numbers of syllables with similar segmental content and carefully matched grammatical structure (1939, p.85). Subsequent studies have not been kinder to the isochrony hypothesis (Shen and Peterson, 1962; Dauer, 1983; Jassem, Hill and Witten, 1984; Crystal and House, 1990). This is so, despite the strong impressions listeners have that there is often a rhythmic basis to speech. Some have concluded that the perception of rhythmic regularity in speech is a construct, or illusion, probably based on the well known general tendency of the perceptual apparatus to regularize in the face of noise (Lehiste, 1977; Dauer, 1983; Benguerel and D'Arcy, 1986), and, specifically, to hear temporally patterned events as rhythmically structured whether they are or not (Woodrow, 1951; Fraisse, 1956).

In a comprehensive review of work until 1977, Lehiste (1977) listed some of the reasons why many studies had failed to document isochrony. First, the speech material is often largely uncontrolled. Secondly, researchers do not use a uniform framework within which isochrony could be identified. For example, Shen and Peterson (1962) regarded each sentence as having one and only one primary stress, while O'Connor (1965) identified as many as 15 stress groups within a single limerick. Perhaps most importantly, however, it is not clear how much deviation from strict isochrony is permissible, and perhaps required, in sentences perceived to be regular. Benguerel and D'Arcy (1986) have assessed the degree to which deviation from regularity, in the form of phrase-final deceleration, is actually *necessary* for the perception of regularity.

Two further possibilities might be added to Lehiste's list. First, the measurement point, which for most researchers has been the onset of the nuclear vowel of the stressed syllable, needs some amending in the light of the discovery of the P-center ("perceptual center") or stress beat. Under the former name, Morton, Marcus and Frankish (1976) pointed out that series of syllables with isochronous acoustic onsets are not necessarily heard as isochronous. In common with Allen (1972), who used the term stress beat, they found that the perceived beat of a syllable was located near to the onset of voicing, but occurred earlier as a function of the length of the initial consonant cluster, and later as a function of the length of the syllable coda. Models which predict the location of the stress beat have since been proposed (Marcus, 1981; Scott, 1993). In this article we will use the terms beat and stress-beat, but we do not differentiate these from the P-center.

A second possibility which has received less attention is that some beats are silent. Espoused by Abercrombie (1965,1967), this possibility should lead one to look for intervals, not only of length n, but $2n, 3n$ etc. This possibility is missed, for example, by Scott, Isard and de Boysson-Bardies (1985) who derived a measure of irregularity with which they look for evidence of isochrony. The measure they adopted is minimized by successive intervals whose ratios are $1:1$, and is increased by deviations from this ratio. The result is that successive intervals which are related as, e.g., $1.837:1$ are regarded as *more* regular than intervals related as $2:1$, as would be found in a perfectly isochronous series with one silent beat. Failing to consider silent stress beats could have led researchers to prematurely reject the isochrony hypothesis. If silent beats are admitted to the fold, it is obvious that speech rhythm may turn out to be more complex than the degenerate rhythm of a simple isochronous series.

In fact, we do not believe either of the latter two points are likely to cause a complete reinterpretation of the empirical work which has so far failed to document isochrony in English speech. Classé's original observations that isochrony is likely to be very rare in unconstrained speech and that nonetheless its influence continues to be felt, even when largely obliterated by other factors, still ring true (Classé, 1939). This has produced a situation where some investigators have treated speech rhythm as if it were an empirically supported or supportable phenomenon (Couper-Kuhlen, 1993), while others, such as Benguerel and D'Arcy, have pointed out that perceptual regularity by no means entails regularity of the physical stimulus, and have suggested that speech rhythm might simply be unobservable (Benguerel and D'Arcy, 1986, p.244).

If little is known about the physical manifestation of speech rhythm, still less can be said with certainty about its purpose. The establishment of a predictable sequence of alternating strong and weak accents may allow the speaker to generate expectations in the listener which can then be violated with communicative intent (Kidd, Boltz and Jones, 1984). Lehiste argued plausibly that violation of isochrony may be used to signal the presence of a syntactic boundary (Lehiste, 1977), Couper-Kuhlen has claimed that rhythms in conversation may be used to regulate turn taking (Couper-Kuhlen, 1993), while Cutler and co-workers have outlined a role for rhythm in helping listeners perform segmentation of the acoustic signal (Cutler and Mehler, 1993).

We will argue in this paper that rhythm in speech has a more fundamental purpose. Rhythm in any complex motor task serves a coordinative function. By linking disparate motor components together into a single temporal structure, or rhythm, the problem of coordination among the many parts is greatly simplified. This interpretation of rhythm has been best developed in the study of interlimb coordination, both in locomotion and in manual tasks (Schöner and Kelso, 1988b; Diedrich and Warren, 1995), and exemplifies the task dynamic approach to the control of action (Meijer and Roth, 1988; Bingham, Schmidt, Turvey and Rosenblum, 1991).

Within the task dynamic framework, the entire biomechanical apparatus involved in a particular action is understood to function as a single, task-specific, device (Kugler, Kelso and Turvey, 1980; Kelso, Saltzman and Tuller, 1986). From the myriad of complex individual components, a coherent action emerges as a low-dimensional system. The emergence of coherence is only possible because the components have been constrained to act together—they have been *coordinated* (in contrast to the *control* postulated in a motor program approach). In this sense, rhythm can be seen as a coordinative strategy; parts which together produce a rhythm are constrained in their relative timing, reducing the number of degrees of freedom of the system (Bernstein, 1967; Kugler et al., 1980). By way of analogy, consider the four wheels of a car, each of which could in theory point in any given direction. These four degrees of freedom are constrained by the chassis and steering assembly to effectively point along a single trajectory, which in turn is determined by the single degree of freedom of the steering wheel, thus greatly simplifying the control task of the driver.

Speech production requires the coordination of a huge number of disparate biological components, with intrinsic timescales ranging over about three orders of magnitude. Despite the 'slop' attributable to lazy articulation, rate variation, affective factors, etc., the final result is enormously detailed and rich in information. The coordinative principles which enable this feat are what we aim to uncover.

A productive strategy for studying the coordination of complex action systems can be found in the task dynamic approach to rhythmic coordination among the limbs (Kugler et al., 1980; Kelso, Holt, Kugler and Turvey, 1980; Schöner and Kelso, 1988a). The experimental strategy employed within the task dynamical approach to the study of action can be roughly summarized as the establishment of a strictly controlled task (setting up of boundary conditions), the description of the resulting system using a simple collective variable, and the experimental manipulation of that variable through a control parameter. A long series of studies by Kelso and coworkers has examined a small model system which requires the rhythmic coordination of the limbs (Kelso, 1995). Within this paradigm, two fingers or hands (or arbitrary effectors) are wagged cyclically toward and away from the body's midsaggital plane. The wagging task sets very well defined boundary conditions for the action system. Given these constraints, the state of the entire movement system can be succinctly described by noting only the relative phase, ϕ, of the two cycling effectors, that is, the difference between the phases of the two fingers/hands. This collective variable can now be studied under various experimental manipulations. Most of the initial studies involved the experimental control of rate using a pacing metronome which was gradually stepped up. Thus a control parameter (rate) is used to influence the state of the complex system as described by a low dimensional collective variable (relative phase of the fingers or hands) within well defined boundary conditions (the wagging task).

The principal findings of this research are that subjects have a strong preference for a synchronous phase relation between the fingers or hands, where 'synchrony' means that the limbs move toward and away from the midline simultaneously, with no phase lag ($\phi = 0$). The anti-synchronous phase relation ($\phi = 0.5$), where both move left and then right, is less stable—but much more stable (small variance, insensitivity to perturbation) than any other phase angle between the limbs (Kelso and Kay, 1987; Kay et al., 1991). Furthermore, while both the synchronous and anti-synchronous patterns are stable at slower tempos, an increase in tempo eventually leads to a situation in which only synchrony is stable. Study of the stability properties of each production mode and of the transition between stable modes suggests the existence of an underlying dynamic which is parameterized by rate. The system exhibits two competing attractors at slower rates and a single attractor at fast rates. A detailed mathematical model which derives the observed stabilities and transition properties from two component oscillators (roughly, the fingers/hands) which are non-linearly coupled has been developed. It continues to generate rich predictions about the system behavior (Scholz, Kelso and Schöner, 1987; Scholz and Kelso, 1990; Kelso and Jeka, 1992).

One important variant of the basic experimental task is presented in Yamanishi, Kawato and Suzuki (1980), and, in slightly different form, in Tuller and Kelso (1989). In each case, subjects were asked to tap two fingers in time with an external stimulus—one flashing light per finger—with a fixed phase lag given between the two lights. The entire range of possible phase relations between the fingers can be probed over a series of trials by scanning the target through the range of possible phase lags. The goal was to see if the known stabilities of the autonomous movement system (the two fingers in the absence of an external pacing signal) were still evident when intermediate phase relations were specified by the environment. In Tuller and Kelso's experiment, the stimulus was present during tapping; in that of Yamanishi et al., subjects attempted to reproduce a phase lag from memory. The results, however, were remarkably similar. The most important findings were, first, that subjects tended to produce phases which were biased towards the known stable states of synchrony. That is, target phases were not reproduced accurately; rather, for targets close to 0 or 0.5 the produced phases tended to be between the targets and the stable states. Secondly, the variability of subjects' productions was least around these two values.

A central theme of the above work is that the rhythm (the fixed phase relationships between the components of the system) arises from the coupling between the components, while the coupling greatly simplifies the task of coordination among those components. The rhythmic constraints are thus evidence of the coordinative mechanism underlying a task specific device. Beyond this fundamental observation, the experimental procedure of Yamanishi et al. (1980) and Tuller and Kelso (1989) will be readily seen to be closely related to the experiments detailed herein. The importance of this particular type of experiment lies in the observation that the dynamics of the autonomous system (the movement system comprising two oscillating fingers or hands) are apparent even in the presence of the externally imposed timing signal. Observed phases gravitate towards attractors of the system and variance is lowest for targets near those attractors.

Our strategy will be to infer the attractor states of the speech production system in a given task from data obtained in the presence of an external timing signal. These attractors will be seen to correspond to readily identifiable rhythmic patterns. We will thus demonstrate that speech rhythm is not only observable using a fairly crude measurement procedure, but it is, indeed, a strong constraint on the organization of stresses *under certain speaking conditions*. In order to uncover these constraints, it is necessary to devise a model speech task which tests the degree to which *arrhythmical* speech is possible. This is described in the next section.

2 Speech cycling: the coupling of speech and stimulus

In our recent work, we seek to develop an experimental paradigm for the study of speech coordination which is directly analogous to the empirical work on coordination among the limbs described above. This requires defining a highly constrained speaking task, within which we can identify a relevant collective variable. Our basic strategy has been to ask subjects to produce speech in time with a given stimulus. In the simplest form of the speech cycling task, subjects are asked to repeat a short phrase in time with an isochronous auditory beep. Under almost all circumstances, a "Harmonic Timing Effect" is observed, whereby the onsets of stressed syllables are found to lie at points within the overall phrase repetition cycle which divide the cycle into simple integer ratios. For example, an onset which recurs half way through the cycle (at phase $\phi = \frac{1}{2}$) will form

Insert Figure 1 about here

Figure 1:

an isochronous beat train with those beats which are associated with the beginning of the phrase. This result is equivalent to the observation of Classé (1939) that a succession of closely matched phrases will, indeed, exhibit a regular rhythm. Beats at $\phi = \frac{1}{3}, \frac{2}{3}, \frac{1}{4}$ etc. of the cycle are also found. Any and all of these cases can be interpreted as examples of isochronous series if, as Abercrombie suggested, the series can include silent beats as well (Abercrombie, 1965).

An alternative interpretation which we propose, is that these simple divisions of the repeating cycle result from the emergence of a harmonic relationship between the cycle of the metrical foot and the phrase repetition cycle (PRC). By 'harmonic,' we mean the establishment of two periodicities which are related as simple multiples. This interpretation requires that we posit both the foot (defined here strictly as the interval between stress beats) and the PRC (which is an artifact of the task) as units in the production of speech under these conditions. As production units, they each have an intrinsic dynamic, and these dynamics can be mutually coupled (Sternberg, Knoll, Monsell and Wright, 1988; Port, Cummins and Gasser, 1995).

This dynamical interpretation of the speech cycling task suggests why isochrony should be more readily observable within the confines of a repetition task than in normal conversational speech. Repetition generates a stable cycle to which nested processes can (or must) entrain. The changing demands of unconstrained speech production do not allow this stability to persist, though it would emerge occasionally as the speech content permitted.

In its simplest form, the speech cycling task provides a stable period, within which nested and entrained periods can be seen to emerge. This approach is currently under development as a method for characterizing cross-language differences in rhythmic structure (Tajima and Port, mspt in preparation). Another strategy, adopted here, is to provide two, potentially conflicting, periods, and thus to assess the limits of the speaker's ability to produce *irregular* speech rhythms. Repetition of a short phrase establishes conditions ideally suited to eliciting isochrony; we wish to establish the extent to which any other pattern is possible.

All of the foregoing has begged the question of measurement. Our algorithm for locating the "beat" of a syllable is given in the appendix. In essence, we examine the energy over the frequency range of the first two formants to identify the rise at the onset of the nuclear vowel. A beat is located halfway through this rise. This gives a consistent measure which can be largely automated; it is similar to the P-center location algorithm of Scott (1993). An example of the beats determined using this procedure is given in Figure 1.

3 Experiment 1a: phrases as simple rhythmic structures

Consider the phrase "beg for a dime" repeated continuously. The phrase repetition cycle (PRC) is the interval from the beginning (or first beat) of one phrase to the beginning of the next. The monosyllables "beg" and "dime" each receive some degree of stress, so that we can identify two metrical feet within the PRC: one from "beg" to "dime" and another from "dime" to "beg". Under most circumstances, repeating this phrase will cause "dime" to fall halfway through the PRC, producing a reasonably isochronous series of beats. This first experiment probes the degree to which other, less rhythmical, patterns are possible. Following Tuller and Kelso (1989), subjects repeat a phrase together with an external pacing signal. As in Yamanishi et al. (1980), they also repeat the phrase after the stimulus is switched off.

Insert Figure 2 about here

Figure 2:

3.1 Method

3.1.1 Stimuli

The stimuli in this experiment were sequences of 14 pairs of alternating short tones. The initial tone was a 1200 Hz tone of 50 ms duration which was sinusoidally ramped over its initial and final 10ms to avoid transients. The lower tone was similar, at 600 Hz. The interval between the high and low tones was fixed throughout this experiment at 700 ms. The independent variable manipulated was the relative time of the low tone within the cycle defined by the high tones. This relative time is measured using a phase convention of $0 < \phi < 1$, so that a phase of 0.5 would mean that the interval between low and high was the same as that between high and low. For each trial, a target phase value (ϕ_{target}) was drawn from a random uniform distribution between 0.3 and 0.7. The low–high interval was then calculated such that the low tone now occurred at the target phase of the cycle whose end points were defined by the succession of high tones (See Figure 2). This gave a high–high cycle length within the range 1.0 sec (for a target phase of 0.7) to 2.333 sec (for a target of 0.3). Stimuli were played at a self-selected comfortable listening level over headphones. The intensity of the last two pairs of tones were scaled down by factors of 0.66 and 0.33, respectively, so that the tones faded out rather than stopping abruptly.

3.1.2 Speech materials

A corpus of 30 short phrases with essentially identical prosodic structure was compiled. Each phrase was of the form *X for a Y*, where *X* and *Y* were each CVC words subject to the following constraints. The initial consonant was one of /b, d, g/. These were selected because the P-center literature suggests that the beat of a syllable is particularly close to the vowel onset when the initial consonant is a voiced stop (Fowler, 1977; Scott, 1993). We also wished to avoid partial devoicing of the vowel onset, as might occur with voiceless stops, because the measurement procedure outlined above is dependent upon voicing. The vowel was either short, from the set {ɛ, ɪ, ʌ}, or long, from the set {i, aɪ, eɪ, oʊ, u, aʊ}. The final consonant came from the set {p, m, f, v, t, d, n, s, z, k, g}. Long and short vowels were counterbalanced with the three initial consonants, and all words were real English words, though the resulting phrases were usually meaningless. This arrangement ensured that our results were not dependent on the narrow segmental makeup of the phrases. Sample phrases include "big for a duck" and "geese for a duke".

3.1.3 Procedure

Four subjects took part, three female and one male, between 20 and 34 years of age. All were speakers of relatively standard American English. Subjects first filled out a standard questionnaire which established dialectical history, musical experience and experience with other rhythmic tasks such as juggling, ballroom dancing etc. The three female subjects were all accomplished musicians. The male subject was a non-musician.

On each trial, subjects were presented with one of the phrases on a screen. They were instructed to listen to the first two pairs of tones, and then to join in, repeating the given phrase in time with the tones, such that the first word of the phrase lined up with the higher of the tones, and the last word lined up with the lower of the tones. They were to attempt to line up their productions

Insert Figure 3 about here

Figure 3:

as accurately as possible with the stimulus. The stimulus consisted of 14 pairs of tones, so 12 repetitions (less any breath pauses, as described below) were obtained together with the stimulus. After the stimulus stopped, subjects continued to repeat the phrase for approximately another 12 repetitions, trying to maintain the timing pattern established together with the stimulus. They were then signaled to stop.

Initial pilots had shown that allowing subjects to breathe in an unconstrained fashion sometimes resulted in a small gasp-like breath being taken on every cycle, which introduced a bias in the timing of events within the cycle. For this reason, subjects were instructed to breathe in, then repeat the phrase, and to skip a whole cycle when they next needed to breathe. They were trained in this breathe–repeat—breathe—repeat task until they felt that they could concentrate again on the task at hand while fulfilling the breathing constraint.

Each subject completed 30 trials per session and 3 sessions on three different days. Each experimental session began with a practice run in which the breathe–repeat task was rehearsed. There were thus 90 trials per subject, with approximately 24 repetitions per trial, less breath pauses.

3.1.4 Measurement

Beats for the initial and final syllables of each phrase were automatically extracted using the algorithm given in the appendix, and then checked against a visual display of beat and amplitude envelope. Where automatic extraction failed (very few cases), measurements were made by hand using a display of both the amplitude envelope and the audio waveform. No phase measurements were made for cycles during which subjects stopped to breathe. Initial examination of the time series data for each trial suggested edge effects for the first one or two repetitions, with stationarity reached thereafter. Occasionally, the stimulus cessation would also cause a particularly variable interval. For these reasons, the first two phase measurements both with and without the stimulus were discarded. The task induced some speech errors. Where these were very obvious, the data were excluded, but the remaining data included a small number of apparent outliers arising from occasional dysfluencies during repetition. Because of the presence of outliers, the median phase per trial ($\hat{\mathbf{\Phi}}$) is used below rather than the mean.

3.2 Experiment 1a: results

3.2.1 Overall distribution of observed phases

The first and simplest hypothesis to be tested is that there are no rhythmic constraints on speech production. If this is so, subjects should be able to locate the onset of the final stress at any given point within the PRC. Their productions should thus mirror the distribution from which the targets were drawn. Figure 3 presents the distribution of $\hat{\mathbf{\Phi}}$, median phase per trial, for each subject. There are 90 trials per subject, with about 18 observations per trial median. In no case do subjects produce anything like the uniform distribution from which the targets are drawn. Rather, the histograms are markedly multimodal, with three clear modes in three cases and two in the fourth (subject KA).

3.2.2 Consistency within and between subjects

At this point, it seems prudent to ascertain whether subjects are consistent in their productions, both within subject from one experimental session to the next, and between subjects. One simple measure of consistency is to compare the sample distributions of observed phases using the Kolmogorov-Smirnov test for goodness of fit. In the usual one sample version of this test, the null hypothesis tested is that a given sample distribution comes from a hypothesized underlying distribution. In the two sample form applied here, the second sample plays the role of the hypothetical distribution. The samples used are the distributions of $\hat{\mathbf{\Phi}}$ obtained over 3 sessions of 30 trials each. Table 1 shows p-values for a Kolmogorov-Smirnov goodness of fit test between each two experimental sessions within each subject. A significant p-value would suggest that the subject is not behaving consistently across sessions. None of the p-values are less than 0.2, and so we can conclude that subjects behave consistently across sessions.

Insert Table I about here

Table 1:

A similar pairwise comparison can be made between subjects. Table 2 lists the p-value for each pairing of subjects. Here, it can be seen that there are consistent differences between subjects. In particular, subject KA is very different from all of the other subjects. In what follows, therefore, data from each subject will be considered separately.

Insert Table II about here

Table 2:

3.2.3 Presence vs absence of stimulus tones

Within each trial, approximately half of a subject's productions were obtained together with the auditory stimulus and half were obtained after stimulus cessation, analogous to the procedures of Tuller and Kelso (1989) and Yamanishi et al. respectively. In a previous experiment (Cummins and Port, 1996b), we observed no difference in mean accuracy under these two conditions. This result was surprising enough to bear replicating, as we had initially hypothesized that subjects would be more accurate in their productions when the stimulus was present. In order to test this, an accuracy score for each trial was computed by taking the median absolute difference between observed and target phases for data collected with and without the stimulus (this is similar to the more familiar root mean squared measure, but uses the median instead of the mean). This provides naturally paired observations which can be given a simple t-test. Table 3 lists t-scores, degrees of freedom and p-values. Although our initial intuitions were that subjects should be more accurate when the stimulus was present, our negative findings from the previous experiment led us to use a two-tailed test. Indeed, the results are inconclusive, as one subject appears more accurate with the stimulus and one without. Certainly there is no strong or consistent effect of presence of stimulus tones on median trial accuracy.

Insert Table III about here

Table 3:

Insert Figure 4 about here

Figure 4:

3.2.4 Data clustering

The histograms of Figure 3 suggest that each subject is producing a small number of distinct patterns. They do not, however, show the effect of the target phase. Figure 4 shows the deviation of the median phase per trial from the target phase as a function of the target phase. Perfect performance would result in data points on the line $y = 0$. Instead, we see that the data cluster into distinct groups, corresponding approximately to the modes of the histograms. This clustering is illustrated by the use of different plotting symbols for each cluster. Each of the groups appears to exhibit a strong linear relationship.

In order to examine these groups individually, the data were divided by hand into three clusters per subject (two for subject KA). Within each cluster a local regression line has been fitted. Table 4 lists slope, R-squared, and n for each regression individually, and also gives the value of the intercept with the x-axis.

Insert Table IV about here

Table 4:

Each of the local regression lines has a negative slope. When the target phase lies below the x-intercept of the regression line, the phases produced are larger than the target, while targets larger than the x-intercept elicit smaller values. Within a cluster, then, all productions are biased towards the value of the x-intercept. This constitutes strong evidence for the existence of attractors located roughly at the x-intercepts, with all points of a cluster lying within one basin of attraction.

It can be seen that subjects JG, LU and JT exhibit three attractors each. In 8 of 9 cases, these are located very close to $\frac{1}{3}$, $\frac{1}{2}$ and $\frac{2}{3}$. Only the lowest cluster of JT's data yields a different intercept (0.274). For subject KA (the only male and non-musician in the group) the data fall into two clusters only. The separation between the two clusters is not as clean as with the other subjects, and the linear fit is somewhat less compelling. There is no evidence of an attractor above 0.5.

The data from subject JG provide an informative example of clusters which overlap in the x-direction. For a target phase within a small range (approximately 0.58–0.61) the system may be

Insert Figure 5 about here

Figure 5:

pulled toward one or other of two attractors.

3.2.5 Variance as a function of target phase

The task in this experiment is similar to that of Tuller and Kelso (1989) and Yamanishi et al. (1980). In both those experiments, the investigators found that the variance in produced phase was lowest around the stable states of the system (synchrony and antisynchrony) and higher elsewhere. Figure 5 plots the per-trial variance for each subject as a function of the target phase. In each case, a smooth fit to the data has been derived using a locally weighted quadratic regression procedure. The method used is that of Chambers and Hastie (1992), where a fitted curve is built based on a least squares fit on a neighborhood (set here to the nearest 40% of the data points) of each predictor value.

For subjects JG, LU and JT, the variance is indeed lowest at or around the attractors. This is an analog of the pattern found in bimanual tasks where variance is lowest at relative phases of 0 and $\frac{1}{2}$. The great increase in variance for trials with target phases above 0.6 makes subject KA's data hard to interpret.

3.3 Discussion of Experiment 1a

Experiment 1a managed to reveal a great deal of structure to the responses of subjects in a rather unnatural task. The experiment is designed with the goal of seeing just how rhythmically independent the metrical foot (taken here as the interval between two stress beats) can be from a higher level phrase repetition cycle which is imposed by the task. The data are quite striking. No subject comes even close to reproducing the uniform distribution from which target phases are drawn.

For three of the subjects, the evidence speaks strongly for the existence of three attractors. A precise numerical evaluation of these attractors is not possible, but each subject seems to have a strong fixed point near $\frac{1}{2}$, with one attractor on either side, perhaps near $\frac{1}{3}$ and $\frac{2}{3}$. A total of eight of the eleven regression lines fitted produce x-intercepts which are within 0.02 of these three fractional values. The interpretation of the three (in one case, two) observed patterns as attractors is supported on several counts: the histograms demonstrate clearly that subjects are producing only a few discrete forms of behavior; the plot of accuracy as a function of target phase revealed that each of these stable behaviors can be associated with a particular target and that neighboring targets are biased towards these values; and finally, the relative stability of these patterns is emphasized by the drop in trial variance when the targets are close to the attractors.

A somewhat worrying aspect of these data is the fact that the one subject, KA, who differs greatly from the other three is the only male and non-musician in the group. While a very large gender difference seems highly unlikely, it is not at all implausible that musical experience plays a role in these results. The speech cycling task is a very unnatural task, which places rather unusual demands on the subject. These demands involve producing prescribed relative temporal onsets for events, and thus resemble musical tasks.

After they had completed three sessions, subjects were asked to informally report their impressions of the task and whether they thought they had accomplished the set goal of matching syllable to tone. All three musicians reported that they thought they had managed to match the syllable

Insert Figure 6 about here

Figure 6:

Insert Figure 7 about here

Figure 7:

to the tone, even though their data show that this was not the case. Rather, they consistently produced three distinct patterns. Subject KA, on the other hand, reported having great difficulty with the task, and judged himself to have failed in the set task of matching syllables and tones. The high variability of his data testify to his difficulties with the task. Certainly, this task makes demands on the subject which are similar to those required of musicians. In order to balance our subject group for musical skills and gender, a further four subjects were recruited and a smaller version of the experiment was run.

4 Experiment 1b: effect of musical training

4.1 Method

The methods in this experiment were exactly as in the preceding, with the exception that a single session of 30 trials per subject was run. The consistency of the previous subjects across sessions suggested that one session would suffice to see if a strong effect of musicianship was present. The four subjects recruited were two female non-musicians (AN and SP), one male non-musician (BS) and one male musician (JF). A male musician was included to check for a strong effect of gender. The subjects called "musicians" in this study report between 3 and 10 years of formal musical training, with between 8 and 29 years of experience playing a musical instrument, and all currently play at least one instrument and read written music fluently. None of the "non-musicians" currently play an instrument or are fluent readers. None has had any formal music training since high school, and all judge themselves to be non-musicians. A total of 4 musicians and 4 non-musicians took part in Experiments 1a and 1b.

4.2 Experiment 1b: results

As in the previous section, Figure 6 shows the overall distribution of median produced phases. Here, too, no subject comes close to reproducing the uniform distribution from which the targets were drawn. Subjects AN and SP (female, non-musicians) produce data much like the three musicians of Experiment 1a. Subject JF (male, musician) produces a bimodal distribution, somewhat similar to that of the male non-musician of the last experiment. Finally, BS (male, non-musician) produces a trimodal distribution with the lowest of the modes being, perhaps, somewhat ill-defined.

Figure 7 plots $\hat{\mathbf{\Phi}} - \phi_{target}$ as a function of ϕ_{target}. Once more, two or three clusters have been identified for each subject and local regression lines fitted. From this figure it is clear that AN and

Insert Table V about here

Table 5:

SP are almost indistinguishable from subjects LU and JT in Experiment 1a, having attractors at values close to $\frac{1}{3}$, $\frac{1}{2}$ and $\frac{2}{3}$. Both these subjects are non-musicians. Subject JF, by contrast, is a musician, yet his data seem to resemble those of KA, the male non-musician of Experiment 1a in exhibiting two clusters of unequal size. Finally, BS's data are interesting as he shows clear attractor structure at $\frac{1}{2}$ and $\frac{2}{3}$, but the clustering and linear modeling of the data are less compelling for targets below about 0.425.

Table 5 provides values for the x-intercept for each local regression line. Again, all slopes are negative and this time 7 of 11 fits produce intercepts within 0.02 of the three simple fractional values. The R-squared values are again high enough to warrant confidence in the regressions.

Insert Table VI about here

Table 6:

Once more, t-tests on paired observations of the median phase were done to look for any difference in accuracy between those repetitions obtained with the stimulus and those without. Table 6 lists the results, and it can be seen that in no case was there a significant difference. This replicates the finding that the presence of the stimulus does not increase the accuracy of subjects in performing this task.

Insert Table VII about here

Table 7:

Finally, it is interesting to extend the between subject comparison of Table 2 to include these four subjects, as in Table 7. The goodness of fit test reveals the obvious difference of KA and JF from the other 6 subjects. By this measure, these two are also different from one another.

4.3 Discussion of Experiment 1b

Experiment 1a was extended to permit equal sampling of two levels of musical skill. Our motivation was the surprising finding that one subject, KA, who was alone in being male and a non-musician, differed markedly from the three other subjects. The primary concern was that musicianship, or substantial formal musical training might greatly influence the results in a speech cycling task. These results suggest that non-musicians too may produce data which show clear evidence of a small number of attractors at phase values close to expected values.

KA and, here, JF, each showed evidence of only two attractors, at approximately $\frac{1}{3}$ and $\frac{1}{2}$, while all others (with the above caveats about subject BS) seem to have three clear attractors at points which divide the PRC into simple ratios. It seems, therefore, that this task elicits substantial intersubject variability, and that the general rhythmic skill involved may be somewhat correlated with musical training, but may also be present in non-musicians (cf. AN and SP). A high degree of intersubject variability is not very surprising given the unusual nature of the task, which requires the alignment of speech and non-speech sounds at two points in the phrase. Previous researchers have reported subjects who are unable to perform tasks which require alignment of non-speech stimuli (clicks, tones) with stresses in speech. Of 16 subjects required to judge as a "hit" or "miss" the alignment of a single click with a target syllable in a recorded phrase, Allen reported that only 3 were able to produce any coherent responses, one of those 3 being the author himself (Allen, 1972). In tasks in which subjects attempted to align a series of alternating syllables so that a perceptually isochronous series resulted, both Seton and Scott reported that one subject failed to reach a satisfactory even rhythm (Seton, 1989; Scott, 1993).

5 Experiment 2: effect of speaking rate

One of the most important features of the model system studied by Kelso and colleagues is the qualitative change, or bifurcation, which the system undergoes as the rate of finger oscillation is increased. From being a system with two stable states, the system becomes monostable. The more complex case, where the system is coupled to an external pacing signal, has not, to our knowledge, been systematically studied at a range of rates.

Maintaining the analogy between the studies of manual patterns and the speech cycling task, we can ask whether the attractor structure found in the above experiments depends on speaking rate. The location of the attractors and/or their number might conceivably change at faster rates. We thus undertook an initial, exploratory experiment at a faster rate.

5.1 Method

Methods employed were exactly as in Experiments 1a and 1b, with the following specific provisions. The fixed interval (interval a in Figure 2 above) was reduced from 700 ms to 450 ms. This yielded PRC periods ranging from 638 ms to 1500 ms. Four subjects were chosen, two from each part of Experiment 1a (JT, LU, SP and JF), giving two female musicians, one female non-musician and one male musician. A single experimental session was run, this time with 28 target phases evenly distributed between 0.3 and 0.705. Target orders were randomized within a session. The reason for this slight amendment to protocol was to ensure adequate sampling of all regions of the range 0.3–0.7 in as few trials as possible. Of the original stock of 30 phrases, 28 were randomly sampled for each session.

Insert Figure 8 about here

Figure 8:

Insert Table VIII about here

Table 8:

5.2 Experiment 2: results

Figure 8 shows the data clustering and local fits, computed exactly as before, for all four subjects, while the x-intercepts and regression data are given in Table 8. Table 9 shows p-values for a two-sample Kolmogorov-Smirnov Goodness of Fit test in which each subject is compared with their data from Experiment 1a or 1b. It can immediately be seen that Subjects JT and LU exhibit almost no effect of rate. They each show the same attractor structure as in Experiment 1a. Subjects JF and SP each show evidence of two attractors only, in each case the distribution is different from that of Experiment 1b. A goodness of fit test comparing SP with JF failed to reveal any difference in the distribution of their data ($p = 0.944; ns$)

5.3 Experiment 2: discussion

The purpose of this additional experiment was to see if an increase in speaking rate influenced the attractor structure observed in the previous experiment. The reduction of the inter-stress interval within a phrase from 700 ms to 450 ms seemed to push subjects almost to their limits. Nonetheless, two of the four subjects showed unchanged attractor structure. The increased basin of attraction for the attractor at $\frac{1}{2}$ for the remaining two subjects is suggestive of greater stability for the simple isochronous case. Further experiments are planned to test this differential stability.

6 General discussion

The first and simplest goal of the present investigation was to demonstrate that under suitably constrained conditions, speech rhythm is not a perceptual illusion. Using a fairly crude measurement procedure, it has been demonstrated that subjects are not free to place stress beats at

Insert Table IX about here

Table 9:

arbitrary points within the PRC. Rather, they exhibit preferences for points which divide the PRC into simple integer ratios, that is, they show the Harmonic Timing Effect.

While there is a considerable degree of intersubject variability, most of the subjects in this study showed strong preferences for 3 distinct phases within the PRC. We can refer to these as the low, mid and high attractor. In all of the remaining cases, subjects exhibited a low and mid attractor, without a high counterpart. Subjects were never able to place the medial stress beat freely within the PRC.

The reader may demonstrate to herself the three distinct forms of organization documented here by reciting the phrase "beg for a dime" along with a series of evenly spaced beats, say finger taps. The low attractor is demonstrated by aligning "beg" and "dime" on successive beats and leaving the next (third) beat silent. The mid-attractor corresponds to the isochronous case: simply align "beg" and "dime" with alternating beats. The late attractor is demonstrated by introducing an artificial stress on "for", and aligning each of "beg", "for" and "dime" with successive beats.

The evidence here is strongly supportive of the existence of attractors, i.e. privileged states of the system towards which the system will tend, and at which the system is most stable. The presence of attractors, in turn, entails the existence of a dynamic, which is readily seen to be both low-dimensional (our measurements are simple scalar phase values) and task-specific, as the PRC does not exist outside of the speech cycling task. The existence of a task-specific system which exhibits a low-dimensional intrinsic dynamic speaks strongly for a coordinative strategy in which relative phases are highly constrained, which is precisely the role we have suggested for rhythm in speech. In the remainder of this article, we will consider three themes of this argument: the case for the existence of a low-dimensional dynamic, the nature of the task-specific system and the role of rhythm in speech.

The presence of attractors and the existence of a low-dimensional dynamic. In Experiment 1a, we saw that subjects displayed only a few discrete behaviors in an experimental task where they were asked to place a stress beat at a point within a continuous range. They produced two or three phases reliably; intermediate targets yielded productions which were strongly biased towards the preferred phases. These preferred phases were often very close to values of $\frac{1}{3}$, $\frac{1}{2}$ or $\frac{2}{3}$, which divide the PRC into simple integral ratios—an effect we have called the Harmonic Timing Effect. The stability of these preferred phases was underscored by their reproduction at a much faster tempo (Experiment 2) and by the reduction in trial variance at the preferred values (Experiment 1a). Furthermore, although this form of the speech cycling task certainly requires a degree of skill, the effect is seen in both musicians and non-musicians (Experiment 1b). Together, these findings justify the interpretation of the preferred patterns as attractors of a dynamic system which is assembled by speakers in response to the demands of the experimental task.

The nature of the task-specific system. The current study is quite unlike previous attempts to apply the task dynamic approach to speech timing (Kelso et al., 1985; deJong et al., 1993; Vatikiotis-Bateson, 1993), which have typically studied the kinematics of individual articulators. While measurements of the position and velocity of, e.g., the jaw are relatively easy to obtain and provide a rich, continuous data stream, they are limited in scale because of the rate at which articulators cycle, which is typically once per syllable. They do not have periods co-extensive with the domains of English speech rhythm, that is, the metrical foot and larger units. In fact, no single part of the speech production system cycles at these timescales. For the study of rhythm at this level, then, no kinematic variable comparable to jaw position or velocity is available.

For this reason we have chosen to focus our attention on the acoustic signal. We defined the collective variable ϕ which is observable only once per cycle, and found that the distribution of ϕ is highly structured. The next question to be addressed is what kind of system could give rise to the observed data? While modeling work is still outstanding, an initial answer can be tentatively proposed.

If we consider the PRC and the metrical foot to each be non-arbitrary units in the production of speech under these conditions, then each can be said to have its own internal dynamic. As both are cyclic processes, the simplest dynamic we might propose is a second order oscillatory system. We have clearly demonstrated that the periods of the two processes are not independent, suggesting that the two systems are coupled. A further presumption is that the 'natural' period of the foot is smaller than that of the PRC. Under these very general conditions, almost any such system will rapidly settle into a state where the period of the more rapid oscillator (the metrical foot) is nested an integral number of times within the period of the slower (the PRC) (Thompson and Stewart, 1986; Glass and Mackey, 1988). Our collective variable ϕ can then be interpreted as a read out of the phase of the PRC at that point at which the metrical foot cycle has just restarted. This is entirely analogous to the mathematical technique of taking a Poincaré section of a system of two coupled oscillators. Further experimental work is required in order to tease out the nature of the two component oscillatory systems and the coupling function between them. An example of evidence pertinent to uncovering the nature of the underlying dynamic is the observation from Experiment 1a that for a range of target phases, subject JG produced two distinct patterns. This demonstrates that for some targets the system is potentially multistable. We have also previously demonstrated the presence of hysteresis in switching from one target to the other (Cummins and Port, 1996a).

The role of rhythm in speech. The speech cycling task introduced here is a highly artificial task. It stands somewhere on a continuum between reiterant speech and unconstrained speech; it does not eliminate as much phonetic detail as a reiterant speech task, but it still contains an artificially repetitive element. It seems reasonable, therefore, to ask about the relation between speech elicited under these artificial circumstances and natural speech. That is, if it be granted that we have demonstrated the presence of strong rhythmic constraints in speech cycling, have we shown anything at all about the role of rhythm in speech? We believe we have.

The very fact that the PRC is an artifact with which subjects have no experience demonstrates that the metrical foot will, of necessity, entrain to a larger cycle. That is to say, in the presence of repetition the speech production system automatically becomes coordinated, such that a higher level dynamic emerges within which the timing of subordinate processes are constrained. In this regard, speech rhythm is no different from the forms of coordination observed in other rhythmic activities (Ostry et al., 1983; Cummins and Port, 1996a). The reader may be familiar with the skill of patting one's tummy and rubbing one's head simultaneously. Once the skill has been acquired it may appear as if the two hands have become decoupled. If however one attempts to continuously alter the rate of one hand, the effect of coupling will rapidly be felt again. Collectively, the hands constitute a higher level system within which the timing of the individual component processes are highly constrained.

One final point is in order about the interpretation of observed rhythmic constraints as rising from coupling between one second-order system (the foot) and another (the PRC). There is nothing in this account which precludes the existence of a temporal unit defined at some other level for speakers of another language. We have studied only English, and have conventionally assumed the metrical foot to be a salient unit in the production of speech for native speakers. Other units might be identified for speakers of Japanese, French, Arabic etc. Indeed, it is conceivable, though unlikely, that a language may have multiple such levels, or none at all.

7 Acknowledgments

This work grew out of a series of fruitful interactions and collaborative projects within the rhythm group at Indiana University. Keiichi Tajima in particular partook of much of the discussion and the development of the speech cycling methodology, but cannot be held responsible for any shortcomings of the present work. We have also benefited greatly from comments by Geoff Bingham, Gary Kidd, Ken de Jong, Mike Gasser, Elliot Saltzman and Betty Tuller. The work was supported by a Research Incentive Dissertation Year Fellowship from Indiana University and a Summer Fellowship from the Cognitive Science Program at Indiana University, both to the first author.

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Appendix A: beat measurement

The present work does not attempt to settle long outstanding questions about the exact location of a beat within a stressed syllable (Allen, 1972; Allen, 1975; Morton et al., 1976; Scott, 1993). It is well known that most subjects can reliably perform a range of tasks which seem to depend on the perception of an instantaneous beat, and while this beat is highly correlated with the onset of the syllable nucleus, it is displaced somewhat as a function of both the initial consonant(s) and the length of the rime (Allen, 1972; Morton et al., 1976; Fowler, 1977; Scott, 1993). In keeping with the work of Allen (1972) we refer to these events as stress beats, or simply beats, but we do not differentiate them from the P-centers sought by other researchers. The deviation of the perceived beat from the onset of a nuclear vowel is small compared to length of the average interstress interval, and so our results should be robust with respect to the details of the procedure outlined below.

The extraction of stress beats is done largely automatically, using an algorithm based on the work of Scott (1993). No claim is made that the beats extracted here are more accurate than those computed by any other algorithm. However, the algorithm presented here preserves most of the merits of existing procedures, and produces beats close to, but slightly after, the onset of syllabic voicing.

Speech is recorded digitally at 11025 Hz. The signal is bandpass filtered using a first order Butterworth filter centered at 1000 Hz and having a bandwidth of 600 Hz. Because of the shallow skirts of this filter, the net effect is to largely eliminate fricative noise and F0 energy, leaving energy in the formant regions intact. Informal trials with a range of filters indicated that any procedure which achieved these dual goals would suffice. The resulting signal is rectified (using absolute values) and smoothed heavily, usually using another first order Butterworth filter, this time as a lowpass filter with a very low cut off of about 10 Hz. The result of this stage is a smooth amplitude envelope. A beat is associated with every local rise in this envelope, and is defined as occurring at the point in time midway between the points where the local rise is 10% and 90% complete. This is similar to the heuristic used in Scott (1993), and serves to remove the effect of very gradual on- and offsets. Figure 1 illustrates beat placement for a sample phrase. The resulting beats are marked graphically in a display of the amplitude envelope, and are then checked visually for reasonableness and completeness. Both criteria are necessary as spurious beats may be detected, e.g. halfway through a diphthong, and beats may be missed, as when a syllable is partly or wholly devoiced. In the latter case, measurements are made by hand from the amplitude envelope, with the acoustic signal as a guide. No attempt is currently made to assign a relative strength to a beat, although this is, in principle, possible.

Table I

	Session 1 and 2	Session 1 and 3	Session 2 and 3
JG	0.239	0.594	0.808
LU	0.594	0.808	0.594
JT	0.808	0.808	0.594
KA	0.808	0.393	0.594

P-values for two-sample Kolmogorov-Smirnov Goodness of Fit test. Sample distributions are $\hat{\mathbf{\Phi}}$ from a single session. Comparisons are within subject, across sessions. No *p*-values are significant, indicating that subjects are consistent in their behavior across experimental sessions.

Table II

	JG	LU	JT	KA
JG	–	0.402	**0.0232**	**<0.001**
LU		–	0.164	**<0.001**
JT			–	**<0.001**

P-values for two-sample Kolmogorov-Smirnov Goodness of Fit test. Sample distributions are per-subject; each subject's data contain $\hat{\mathbf{\Phi}}$ from three experimental sessions. Significant *p*-values are in bold font.

Table III

Subject	t	df	p
JG	1.47	89	0.145
LU	-2.04	89	**0.0439**
JT	3.72	89	**<0.001**
KA	-1.62	89	0.109

T-tests for paired observations, comparing data obtained with and without the stimulus. Each datum is the median absolute difference between observed phase and target phase. All tests are two-tailed.

Table IV

sub	x-int	slope	R^2	n	x-int	slope	R^2	n	x-int	slope	R^2	n
JG	0.333	-0.334	0.553	41	0.491	-0.712	0.747	22	0.654	-1.05	0.951	27
LU	0.321	-0.632	0.891	29	0.48	-0.774	0.669	27	0.646	-1.02	0.875	34
JT	0.272	-0.416	0.538	37	0.482	-0.605	0.566	22	0.657	-0.702	0.644	31
KA	0.275	-0.604	0.771	27	0.424	-0.610	0.747	63	—	—	—	—

Regressions in Experiment 1a. For each data set, 3 clusters have been estimated and a local regression line fitted to each. Listed here are values of the x-intercept, slope, R-squared and n for each regression.

Table V

sub	x-int	slope	R^2	n	x-int	slope	R^2	n	x-int	slope	R^2	n
AN	0.34	-0.432	0.689	12	0.509	-0.634	0.690	10	0.716	-0.607	0.714	8
SP	0.324	-0.816	0.629	8	0.490	-0.828	0.911	15	0.656	-1.26	0.573	7
JF	0.229	-0.326	0.446	9	0.492	-0.731	0.870	21	—	—	—	—
BS	0.305	-0.224	0.249	14	0.472	-0.598	0.845	10	0.643	-0.928	0.892	6

Regressions in Experiment 1b. For each data set, clusters have been estimated and a local regression line fitted to each. Listed here are values of the x-intercept, slope, R-squared and n for each regression.

Table VI

Subject	t	df	p
AN	1.28	28	0.210
SP	-1.09	29	0.284
JF	-0.983	29	0.334
BS	1.13	29	0.267

T-tests for paired values, comparing data obtained with and without the stimulus. Each datum is the median absolute difference between observed phase and target phase. A total of 30 trials (in one case, 29) were run for each subject. All tests are two-tailed.

Table VII

	JG	LU	JT	KA	AN	SP	JF	BS
JG	–	0.402	**0.0232**	**<0.001**	0.0968	0.377	**0.0308**	0.377
LU		–	0.164	**<0.001**	0.16	0.453	**<0.01**	0.31
JT			–	**<0.001**	0.202	0.31	**<0.01**	0.31
KA				–	**<0.001**	**<0.001**	**<0.001**	0.31
AN					–	0.594	0.135	0.239
SP						–	0.393	0.135
JF							–	0.135

P-values for two-sample Kolmogorov-Smirnov goodness of fit test. Each pair of sample distributions comes from two subjects. Significant p-values are in bold font.

Table VIII

sub	x-int	slope	R^2	n	x-int	slope	R^2	n	x-int	slope	R^2	n
JT	0.310	-0.316	0.393	8	0.511	-0.922	0.728	9	0.655	-0.914	0.916	11
LU	0.355	-0.691	0.894	8	0.522	-0.810	0.841	10	0.667	-1.148	0.943	10
SP	0.349	-0.378	0.455	6	0.548	-0.646	0.841	22	—	—	—	—
JF	0.378	-0.693	0.583	6	0.542	-0.563	0.845	22	—	—	—	—

Regressions in Experiment 2. For each data set, two or three clusters have been estimated and a local regression line fitted to each. Listed here are values of the x-intercept, slope, R-squared and n for each cluster.

Table IX

Subject	p
JT	0.200
LU	0.072
SP	**0.010**
JF	**0.012**

Results of a Kolmogorov-Smirnov Goodness of Fit test comparing each subject's data in Experiment 2 with that of Experiment 1).

Figure Legends

Figure 1 Beats extracted from the phrase "Big for a duck" repeated twice. Top panel: Acoustic signal. Lower panel: smoothed amplitude envelope and beats. For the task reported here, only the first and third beat of each group of three were considered.

Figure 2 Stimulus used in Experiment 1. A succession of 14 pairs of alternating high (H) and low (L) tones are used. The interval from high to low tone, a, is fixed at 700 ms. The target phase, or relative time of occurrence of the low tone, is set by manipulating the interval from low to high tone, b.

Figure 3 Distributions of $\hat{\mathbf{\Phi}}$ for phrase final syllables. Each data point is a trial median, with about 18 observations per trial. There are 90 trials per subject. Target phases were drawn from a uniform distribution between 0.3 and 0.7.

Figure 4 Difference between $\hat{\mathbf{\Phi}}$ and ϕ_{target} for each trial plotted as a function of the target phase. Perfect performance would yield data points on the line $y = 0$ (dotted line). Clusters have been extracted by hand from each data set and a local regression line fitted. For illustrative purposes, different plotting symbols have been used for data points within each cluster.

Figure 5 Trial variance as a function of target phase. For each subject, a locally weighted quadratic regression curve has been fitted using a weighted least squares fit on a neighborhood of 0.4 of the total number of data points.

Figure 6 Distribution of $\hat{\mathbf{\Phi}}$ by subject. There are 30 trials per subject, and target phases come from a random uniform distribution between 0.3 and 0.7. Subjects AN, SP: female, non-musicians; Subject JF: male, musician; Subject BS: male, non-musician.

Figure 7 Distribution of $\hat{\mathbf{\Phi}} - \phi_{target}$ as a function of ϕ_{target}. Subjects AN, SP: female, non-musicians; Subject JF: Male, musician; Subject BS: Male, non-musician. As before, clusters have been estimated within each data set and a local regression line fitted. Plot symbols refer only to cluster membership.

Figure 8 Distribution of $\hat{\mathbf{\Phi}} - \phi_{target}$ as a function of ϕ_{target}. Subjects JT, LU: female, musicians; Subject SP: female, non-musician; Subject JF: male, musician. As before, clusters have been extracted and local regression lines fitted.

Figure 1

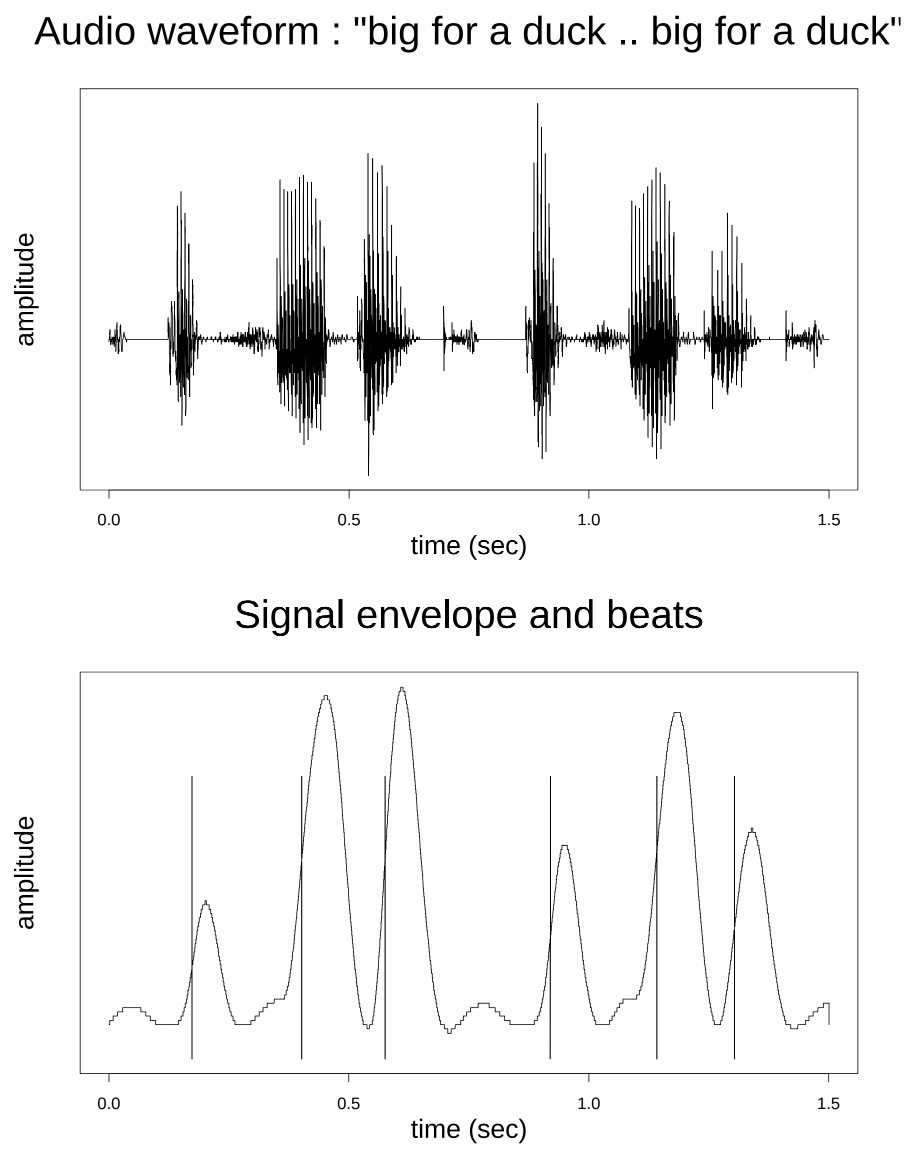

Audio waveform : "big for a duck .. big for a duck"
amplitude
0.0
0.5
1.0
1.5
time (sec)
Signal envelope and beats
amplitude
0.0
0.5
1.0
1.5
time (sec)

Figure 2

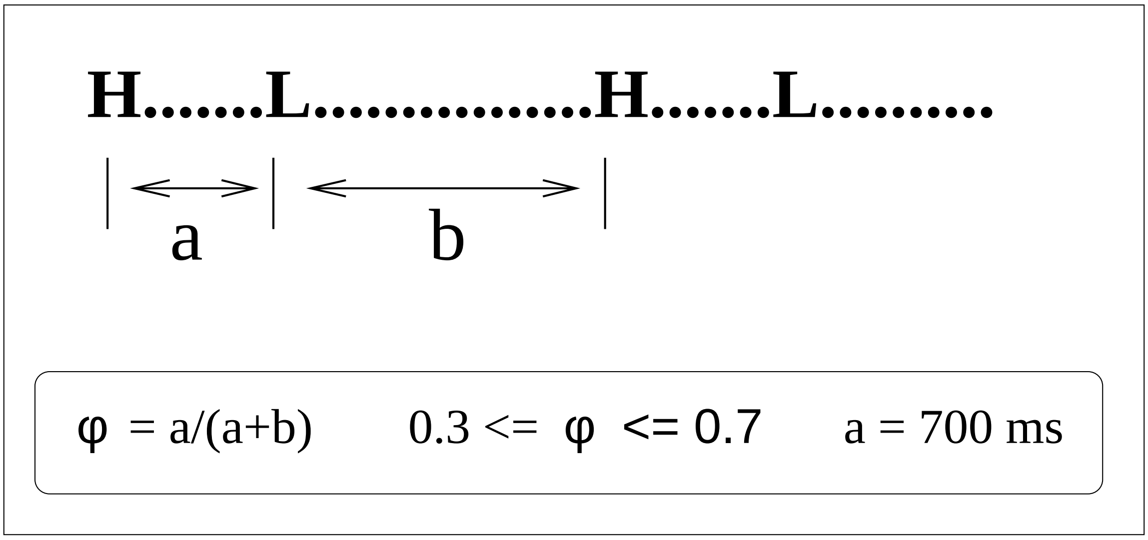
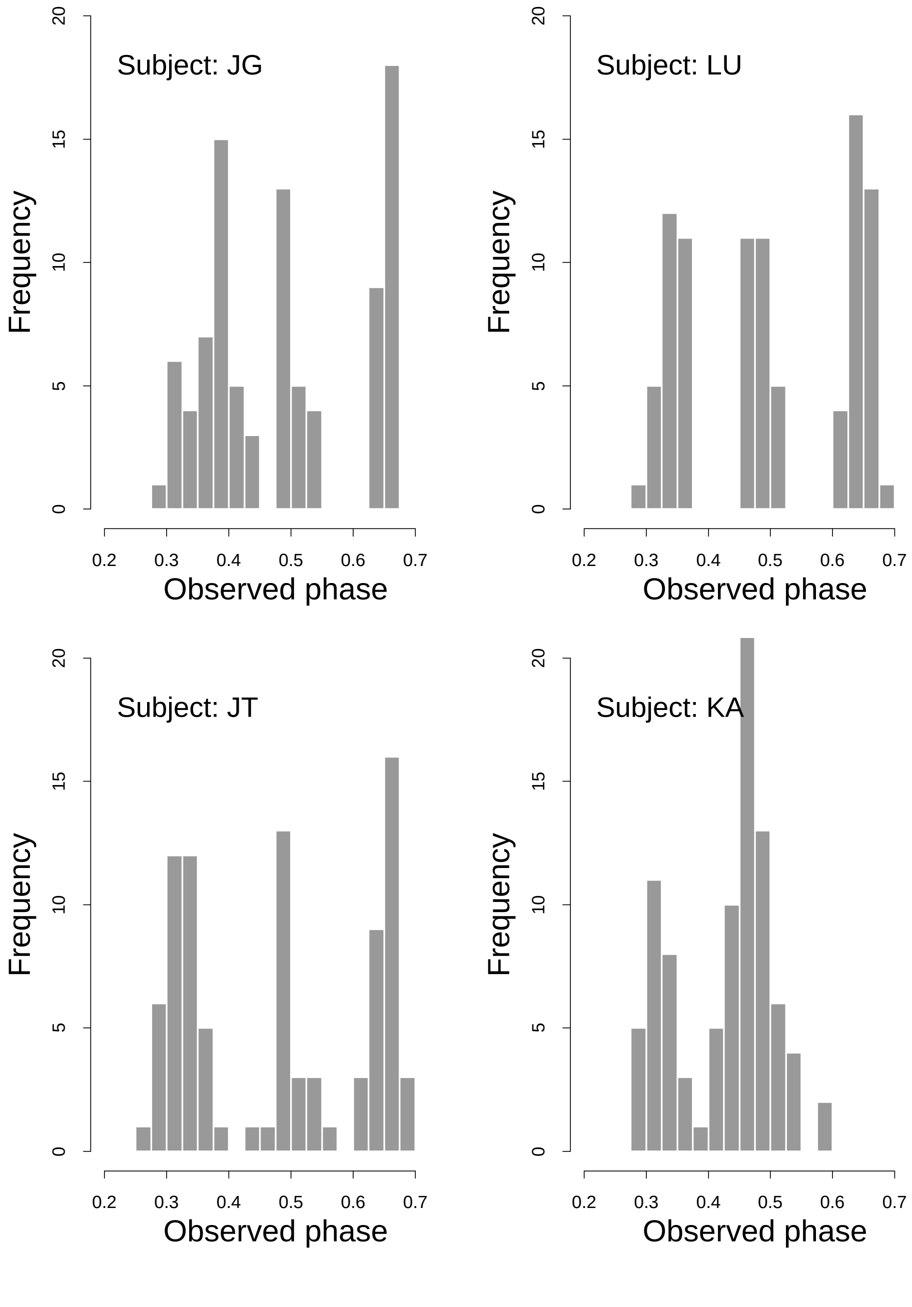


Figure 3



Subject: JG
Frequency
Observed phase
0
5
10
15
20
0.2
0.3
0.4
0.5
0.6
0.7
Subject: LU
Subject: JT
Subject: KA

Figure 4

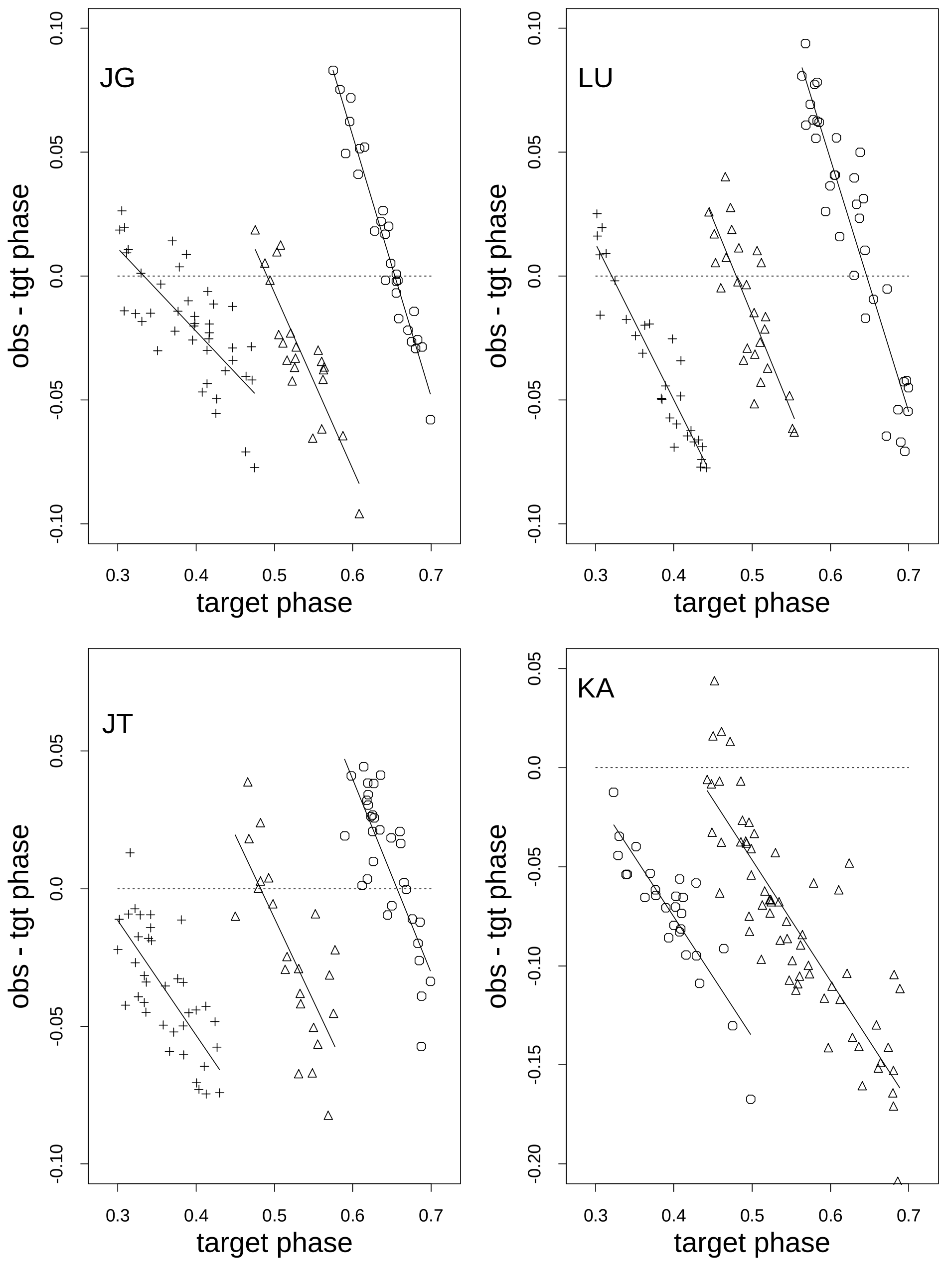
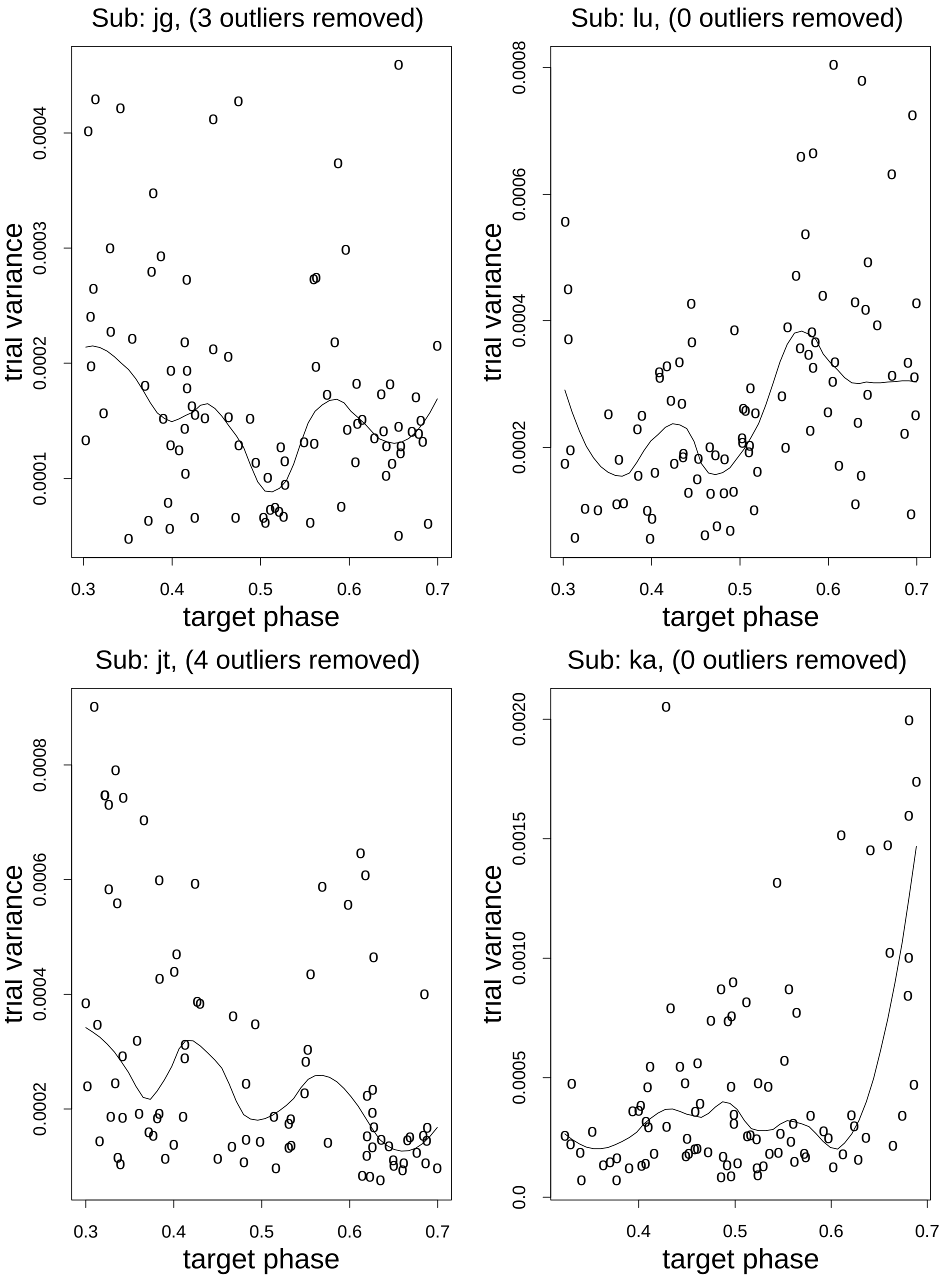


Figure 5



Sub: jg, (3 outliers removed)
trial variance
0.0001
0.0002
0.0003
0.0004
target phase
0.3
0.4
0.5
0.6
0.7
Sub: lu, (0 outliers removed)
trial variance
0.0002
0.0004
0.0006
0.0008
target phase
0.3
0.4
0.5
0.6
0.7
Sub: jt, (4 outliers removed)
trial variance
0.0002
0.0004
0.0006
0.0008
target phase
0.3
0.4
0.5
0.6
0.7
Sub: ka, (0 outliers removed)
trial variance
0.0
0.0005
0.0010
0.0015
0.0020
target phase
0.4
0.5
0.6
0.7

Figure 6

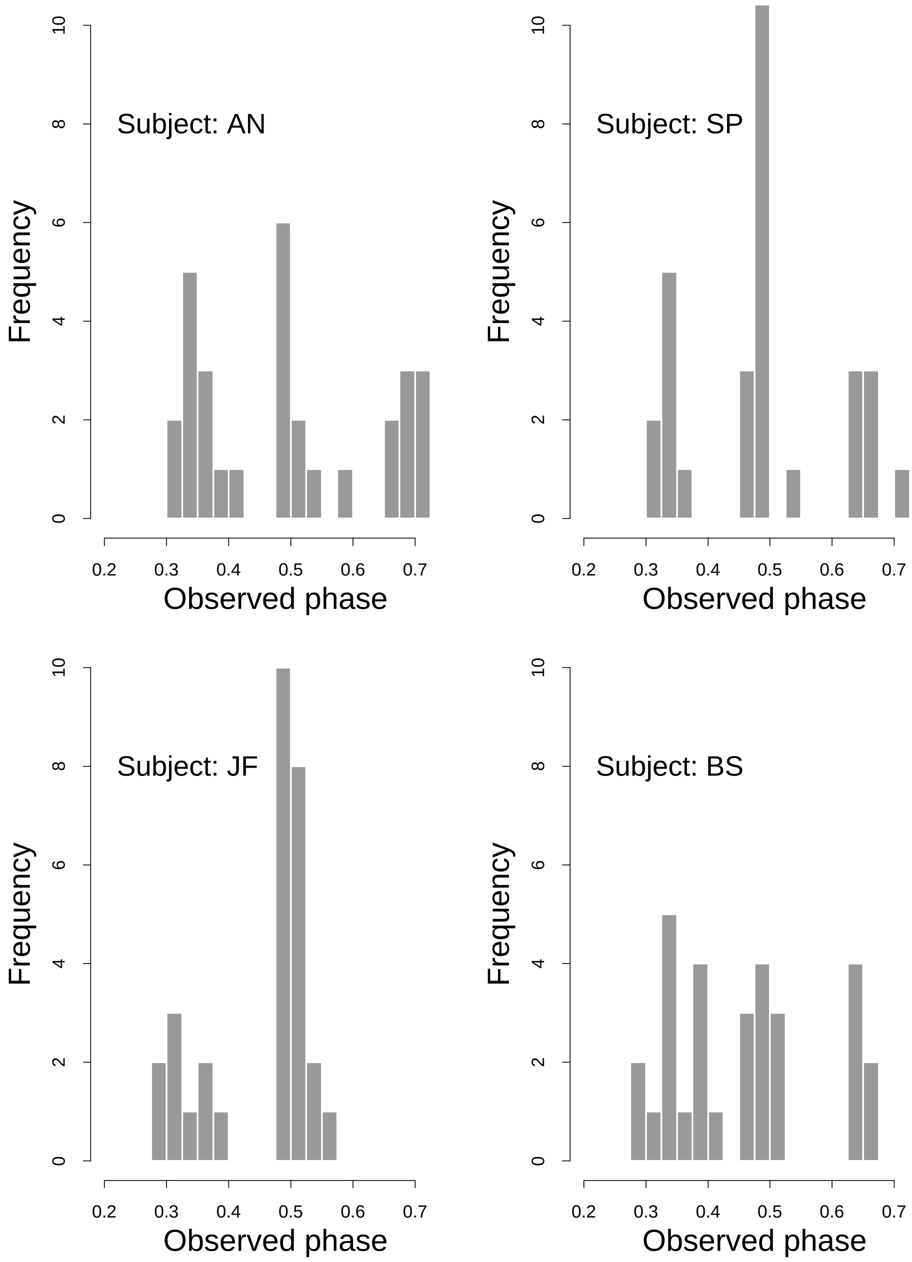

Subject: AN
Subject: SP
Subject: JF
Subject: BS
Frequency
Observed phase
0
2
4
6
8
10
0.2
0.3
0.4
0.5
0.6
0.7

Figure 7

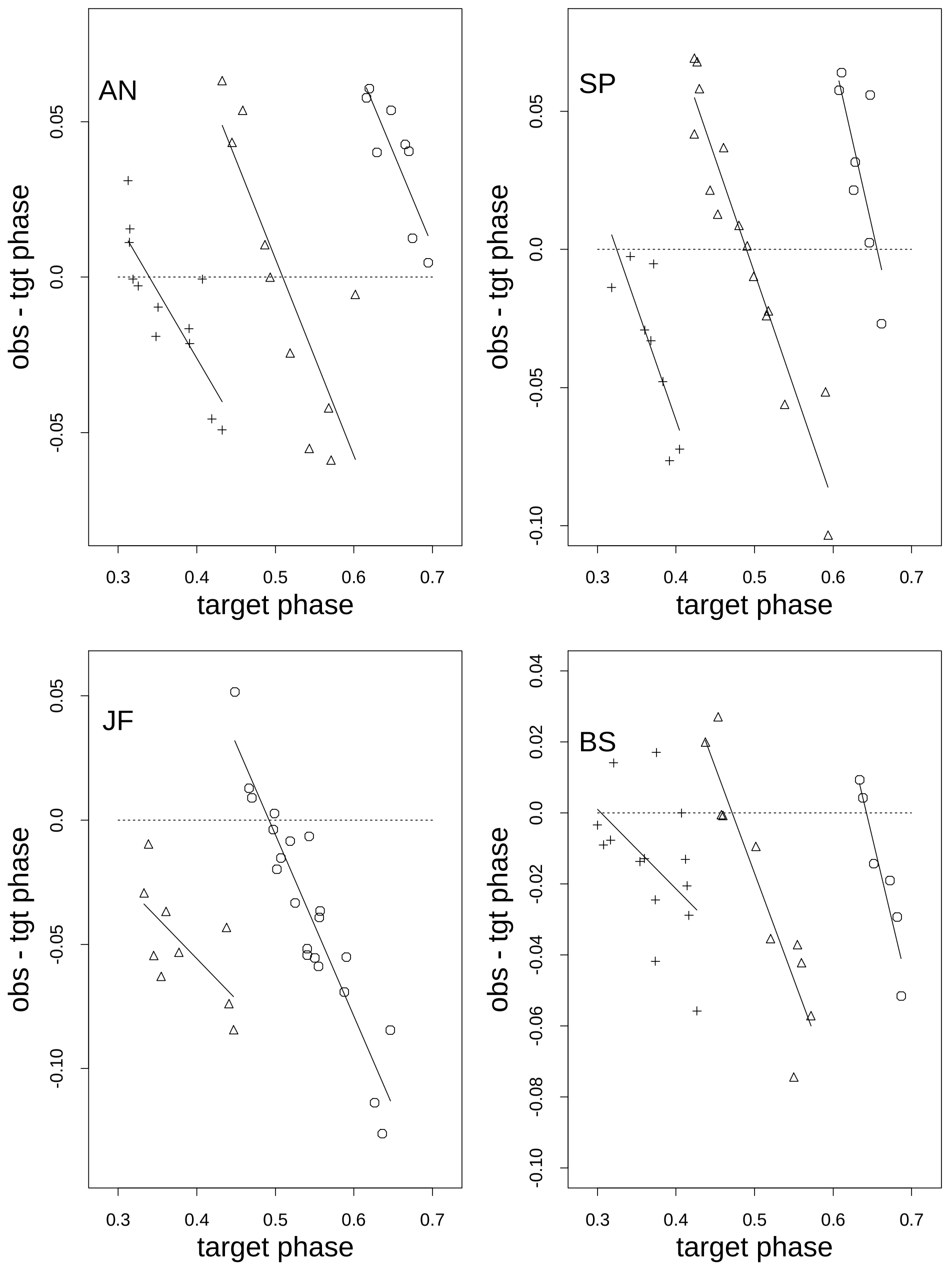

AN
SP
JF
BS
obs - tgt phase
target phase
0.3
0.4
0.5
0.6
0.7
0.05
0.0
-0.05
-0.10
0.04
0.02
-0.02
-0.04
-0.06
-0.08

Figure 8