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Temporal coordination between actions and sound during sequence production

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Abstract

Delayed auditory feedback (DAF) causes asynchronies between perception and action that disrupt sequence production. Different delay lengths cause differing amounts of disruption that may reflect the phase location of feedback onsets relative to produced inter-response intervals, or the absolute temporal separation between actions and sounds. Two experiments addressed this issue by comparing the effects of traditional DAF, which uses a constant temporal separation, with delays that adjust temporal separation to maintain the phase location of feedback onsets within inter-response intervals. Participants played simple isochronous melodies on a keyboard, or tapped an isochronous beat, at three production rates. Disruption was best predicted by the phase location of feedback onsets, and diminished when feedback onsets formed harmonic phase ratios (phase synchrony). Both delay types led to similar effects. Different movement tasks (melody production versus tapping) led to slightly different patterns of disruption across phase that may relate to differing task demands. In general, these results support the view that perception and action are coordinated in relative rather than absolute time.

PsycINFO classification: 2330; 2320

Keywords: Delayed auditory feedback; Rhythm; Sequence production; Music performance; Relative phase; Perception and action

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1. Introduction

When people produce meaningful auditory sequences, by speaking or playing a melody on the keyboard, they are both producers and perceivers of the sequence they create. Various researchers have explored the role of self-perception (termed 'auditory feedback') by altering auditory feedback during production (for a recent review focusing on speech, see Howell, 2004, for a recent review focusing on music, see Pfordresher, 2006). When disruption of production results (e.g., by increases in error rates or slowing of timing relative to production with normal feedback), the implication is that the alteration modified an important characteristic of perception/action coordination.

The most extensively studied feedback alteration concerns timing (synchrony) of perception and action: Delayed Auditory Feedback (DAF). In this paradigm a constant time lag is inserted between produced actions (e.g., a piano keypress) and the onsets of auditory feedback events (e.g., the onset of a pitch). Such alterations significantly disrupt production (first discovered in speech by Black, 1951; Lee, 1950; first reported in music performance by Havlicek, 1968; see Yates, 1963 for a review of early research). Typically, the amount of disruption increases with delay length up to a certain length at which disruption reaches a maximum. Pfordresher (2003) demonstrated that disruption of music performance by asynchronous delays is specific to the timing of produced inter-response intervals (IRIs) rather than the accuracy of response selection (key presses). Although DAF disruption clearly reflects temporal coordination of actions and sound, the basis of the coordination has been debated.

According to one hypothesis, here referred to as the *relative time hypothesis*, perception and action are coordinated according to the rhythmic cycles formed by IRIs (cf. Jones, 1976). Events, in this context, may refer to actions (key presses) or sounds. This view predicts that disruption from asynchronous feedback should vary with the phase ratio of auditory feedback onsets relative to IRIs. Thus, the relative time hypothesis predicts that the disruptive effect of a single delay length will vary with production rate (tempo). Moreover, disruption should be reduced for simple phase ratios, such as phase synchrony (e.g., when delay length is equal to the IRI) and (possibly) antiphase relationships (when feedback onsets bisect IRIs). Recent support for the relative time view was found by Finney and Warren (2002) who demonstrated that the disruptive effects of specific delay lengths on rhythmic tapping varied with production rate (see also Robinson, 1972). In addition, Pfordresher and Palmer (2002) found some evidence for the idea that disruption is alleviated at simple phase ratios, specifically antiphase coordination between actions and feedback onsets. Theoretically, the relative time hypothesis converges with theories that link disruption to rhythmic interference, such as the rhythmic displacement hypothesis (Howell, Powell, & Khan, 1983), and with dynamical systems views that assign a prominent role to relative phase in the production and perception of rhythms (e.g., Kelso, 1995; Large & Jones, 1999).

An alterative view, termed the *absolute time hypothesis*, holds that disruption occurs when the time lag between a produced action and the resulting feedback event falls within a certain window. This view stems from the fact that disruption from DAF is often maximal for delays around 200 ms (e.g., Black, 1951; Fairbanks & Guttman, 1958; Howell et al., 1983; MacKay, 1968; see Finney, 1999 for a review), although in music production the maximally disruptive delay may be longer (e.g., 270 ms, found by Gates, Bradshaw, & Nettleton, 1974). In speech production, MacKay (1968; see also Butler and Galloway,

1957) found support for an absolute time view in that disruption from specific delay lengths did not vary with speaking rate (though it did vary with the maximum possible rate of individual speakers). MacKay (1987) has further integrated these findings into a general theory of perception and action, according to which perceived events prime nodes in a network used for perception and production. After a node is activated via production, it enters a recovery cycle in which a phase of inhibition (i.e., of priming by feedback) is followed by a 'hyper sensitive' phase, approximately 200 ms later. DAF disruption is thought to occur because delayed onsets sound during the hyper sensitive phase.

One limitation of most past experiments is that manipulations of auditory feedback synchrony have used fixed delay lengths. In such cases, phase relationships between timing of actions and feedback onsets can vary with production rate, which typically decreases with DAF. Moreover, it is possible that the fact that the ability to control the relative phase of feedback onsets (via production rate) enhances sensitivity to these to phase relationships. Indeed, Pfordresher and Palmer (2002) found that participants tended to position delay onsets in between produced onsets (antiphase) when attempting to adjust tempo to a rate at which the delays felt 'comfortable'. More recently, Pfordresher (2003) reported an experiment that incorporated a new kind of delay for which the delay length varied to maintain a consistent relative phase within IRIs (manipulated using FTAP, Finney, 2001). The research reported here compared the effect of these *adjustable delays* with the effect of *fixed delays*, which maintain a constant time lag like traditional DAF. If patterns of disruption are influenced by parameters that a participant can control (absolute time or relative phase of delays), then it is possible that disruption from adjustable delays would be most related to the absolute time separating actions and auditory feedback (because the participant can adjust absolute time), whereas disruption from fixed delays would be related to the relative phase of feedback onsets.

Another issue relevant to the nature of perception/action coordination concerns the relationship between feedback onsets and the kinematics of production. Many theories (e.g., Hommel, Müsseler, Aschersleben, & Prinz, 2001; MacKay, 1987) associate timing with distal events rather than the movement patterns that lead to events. Thus, DAF disruption should remain consistent when a given rhythmic pattern is produced through different movement regimes. The alternative view, consistent with the rhythmic displacement hypothesis of Howell et al. (1983; cf. Zimmerman, Brown, Kelso, Hurtig, & Forrest, 1988) predicts that disruption should be closely connected to movement itself. The current experiments test these different perspectives by varying the nature of the movement task, to include musical sequence production (on an electronic keyboard), or tapping (on a drum pad). Whereas continuation tapping is characterized by maximal amplitude approximately midway between taps (Balasubramaniam, Wing, & Daffertshofer, 2004), musical keyboard performance involves more complex movements in which the finger associated with a key press is held above the key about two beats prior to production, and then depressed rapidly (Dalla Bella & Palmer, 2004).

The primary goal of the current research was to test the relative and absolute timing hypotheses. In two experiments, participants produced isochronous sequences at different tempi. Each hypothesis predicts different relationships between the factors tempo and delay length, depending on the delay type that a participant experiences. The relative timing hypothesis predicts an interaction between the factors tempo and delay for fixed delays (because phase relationships for fixed delays vary with tempo) but not for adjustable delays, such that disruption is minimal when delay lengths are equivalent to produced

IRIs. Conversely, the absolute timing hypothesis predicts an interaction between delay length and tempo for adjustable but not for fixed delays, such that disruption is maximal for delays around 200–270 ms in length (cf. Gates et al., 1974; MacKay, 1987). Disruption was measured by examining the rate of production during the continuation phase of the trial (in which feedback could be asynchronous) with the synchronization phase (in which feedback was always synchronous).

2. Experiment 1

Participants with varying levels of musical skill (most being musically untrained) produced isochronous sequences at different production rates, in a synchronization/continuation paradigm. The musical sequence task was designed so that musical training was not necessary (cf. Pfordresher, 2005). Participants could experience either fixed or adjustable delays throughout the experiment, and each participant spent half the session engaged in the musical sequence task and the other half of the session engaged in isochronous tapping. Delays in Experiment 1 were designed to be relatively long, forming a distribution around phase synchrony, which according to the relative time hypothesis should lead to a reduction in DAF disruption.

2.1. Method

2.1.1. Participants

Twenty-five adults from the San Antonio, Texas, community participated in exchange for course credit in introductory psychology (mean age = 19.6, range = 17–30). Twelve participants experienced fixed delays and the rest experienced adjustable delays (see Section 2.1.3). Fifteen were female, 10 were male. Twenty-two participants were right-handed, three were left-handed. The only selection criteria were normal hearing and normal motor functioning. Participants reported 3.96 years of experience performing a musical instrument (keyboard or other) or singing (range = 0–14, mode = 0) and 2.12 years of training (range = 0–13, mode = 0) on average. Four participants reported experience playing the piano, 6.63 years of training (range = 2.5–13), and 8.5 years of experience (range = 3–13) on average. Their inclusion did not significantly influence the pattern of results reported here.

2.1.2. Materials

All participants produced the same melody for sequence production trials (from a set described in Pfordresher (2005)). Participants produced the melody with their right hand. The melody comprised eight events selected from five pitch classes (C5-D5-E5-G5-F5-E5-D5-E5) to create an invariant finger-to-key mapping (the fingering was: 1-2-3-5-4-3-2-3, where 1 = thumb of the right hand). Notation displayed a row of numbers corresponding to fingers; above each number was a drawing of a hand with the respective finger highlighted. On the keyboard, the numbers 1–5 were arranged in a row above corresponding piano keys.

2.1.3. Conditions

The main variables of interest comprised delay type, delay magnitude, performance rate (tempo), and movement type. Each delay type was combined with four delay conditions.

Fixed delays could be 0 ms (normal), 330 ms, 500 ms, or 660 ms, and adjustable delays could be 0%, 66%, 100% or 132% of produced IRIs. The combination of tempo with different delay magnitudes influences the relative phase of the delay for fixed delays, but influences the length of the delay for adjustable delays. Delay conditions were chosen to represent a range of values around phase synchrony, and to equate delay length and relative phase for the 500-ms tempo condition. Performance rates (in IRIs) included 330 ms, 500 ms, and 660 ms. The two movement types were musical sequence production and isochronous tapping.

Delay type constituted the single between-participants variable; the rest were varied within participants. Tapping trials were always presented during the first half of the experiment, followed by musical sequence production trials. Six order conditions were created by crossing the following variables in a Latin square design: delay type, order of tempo conditions within the first and second half of the session, and two random orders of trials.

2.1.4. Apparatus

Participants used a Fatar CMK 49 unweighted keyboard for sequence production trials and a Roland SPD-6 percussion pad for tapping trials. Both apparatus were held on the lap. The software program FTAP (Finney, 2001) was used to manipulate auditory feedback, to acquire MIDI data, and to control a Roland RD-700 digital piano that produced auditory output. Participants heard auditory feedback and metronome pulses over Sony MDR-7500 professional headphones at a comfortable listening level. The piano timbre originated from Program 1 (Standard Concert Piano 1), and the metronome timbre originated from Program 126 (standard set, MIDI Key 56 = cowbell) of the RD-700.

2.1.5. Procedure

Each session began with the (easier) tapping trials. Participants were told to tap with the index finger of their right hand in the center of drum pad #2 and to rotate at the elbow. Then participants practiced synchronizing with the metronome at the first tempo, until they demonstrated that they could synchronize acceptably well. Then participants completed a block of trials at this first tempo, followed by two more blocks at the two other tempi. Participants practiced synchronizing with the metronome before each block. After tapping trials were completed, participants completed a questionnaire concerning their musical background.

During the second half of the experiment, participants performed the musical sequence. First the experimenter described the notation system to participants. Participants then performed the sequence repeatedly in view of notation until it was memorized. The notation was then removed for the remainder of the session. Participants then practiced producing the sequence in synchrony with the metronome and went on to complete three blocks of trials (as for tapping trials) with the musical sequence. Each block was preceded by a practice trial.

Each trial incorporated a synchronization–continuation paradigm (Stevens, 1886; Wing & Kristofferson, 1973); altered feedback conditions occurred during the continuation phase. Participants performed each melody repeatedly throughout a trial without pausing between repetitions. During the synchronization phase, participants performed a melody with the metronome and normal auditory feedback. After 16 note onsets (two repetitions of the melody for error-free performances), the metronome stopped, and the participant attempted to maintain that rate during the continuation phase while one of the auditory feedback conditions took place. The continuation phase lasted for another 64 key presses (eight error-free repetitions of the melody), after which feedback ceased. Participants were instructed to adopt a legato (connected) playing style and to avoid correcting any pitch errors.

During normal feedback conditions, feedback events resulted from key presses as they would on an unaltered musical keyboard. During trials with fixed delays, the FTAP program withheld the production of each produced note by a constant time lag. During trials with adjustable delays, FTAP maintained a running average of the previous two IRIs. After each keypress, FTAP withheld production by a percentage of this predicted IRI length.

2.1.6. Data analyses

Analyses focused on timing of IRIs, the time elapsed between successive key presses or taps on the drum pad (in ms). Outliers (defined as IRIs outside a range of 2 standard deviations around the mean) as well as IRIs associated with errors (and IRIs following each error) were removed from analyses.

2.2. Results

An important preliminary issue concerns the degree to which participants were able to synchronize with the metronome, given that our sample primarily included non-musicians. In general, participants were accurate at synchronizing with respect to period (most important for the present research). Mean IRIs during synchronization fell within one standard deviation of the prescribed IRI and only differed from the prescribed tempo by 14 ms on average. Mean asynchronies (time of response – time of metronome onset) were within a similar range to what one would expect in synchronization experiments (mean asynchronies for tapping trials $= -27$ ms, for sequencing trials $= -36$ ms, cf. Aschersleben & Prinz, 1995). Thus we felt justified in assuming that participants' intended production rates matched the prescribed production rates.

We measured disruption through difference scores contrasting mean IRIs in synchronization and continuation (IRI difference $= M_{\text{contin}} - M_{\text{synch}}$). Positive values indicate slowing during continuation (disruption). Other analyses of timing led to similar results that were less robust. Separate within-participants analyses of variance were computed for each combination of delay type (fixed, adjustable) and movement type. Our discussion focuses on main effects of delay amount and interactions of delay with tempo.

Fig. 1a shows mean data for all trials with fixed delays. The Delay × Tempo ANOVA on sequencing trials (Fig. 1a, left), revealed a main effect of delay magnitude, $F(3,33) = 8.04$, $\text{MSE} = 6059.04$, $p < .01$, and a Delay × Tempo interaction, $F(6,66) = 6.12$, $\text{MSE} = 1983.80$, $p < .01$. The same analysis on tapping trials (Fig. 1a, right) yielded no main effects or interactions, due to the minimal disruption found, although the pattern of results was similar. There was a noticeable tendency for disruption to be reduced when mean IRI was equal to the delay length (e.g., delays of 500 ms for the 500-ms tempo condition), as would be predicted by the relative time hypothesis, for five out of six conditions (the 330-ms tempo condition for sequencing trials was the only exception).

Fig. 1b shows analogous results from trials with adjustable delays. For sequence production trials (Fig. 1b, left), there was a main effect of delay magnitude, $F(3,36) = 7.90$, $\text{MSE} = 2736.78$, $p < .01$, but no Delay × Tempo interaction ($p > .10$), as predicted by

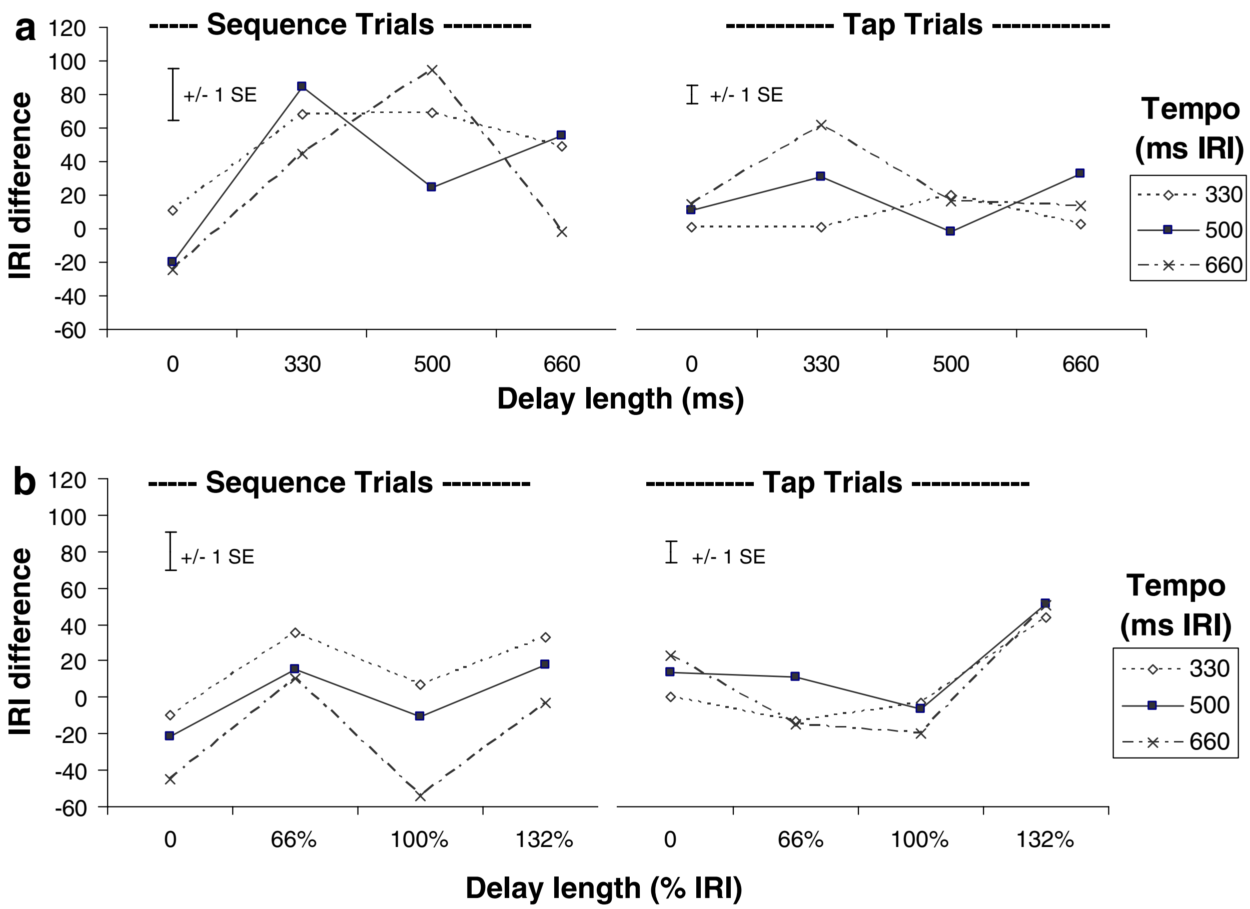

Fig. 1. Experiment 1 differences in mean inter-onset intervals (IRI, continuation–synchronization) as a function of movement type (sequence/tap), prescribed IRI (tempo), and delay magnitude for fixed (a) and adjustable (b) delay types. Error bars represent one standard error of the mean, averaged across conditions.

the relative time hypothesis. For tapping trials (Fig. 1b, right), there was a main effect of delay, $F(3,36) = 9.24$, $\mathrm{MSE} = 2074.86$, $p < .01$, and a Delay × Tempo interaction, $F(6,72) = 2.86$, $\mathrm{MSE} = 706.07$, $p < .05$. The interaction, however, did not match predictions typical of the absolute time hypothesis. In particular, the longest delay phase (132%) was always the most disruptive condition, even in conditions for which that condition resulted in delays that were much longer than 200 ms (cf. MacKay, 1987). Instead, the interaction mostly reflects the fact that participants were not always similarly accurate when tapping with normal feedback, and slowed down during normal feedback conditions in the slowest tempo condition.

Thus far the results of Experiment 1 generally confirm the relative timing view. In order to test the qualitative predictions of this view more thoroughly, all delay conditions for which delay lengths were equal to prescribed IRIs (resulting in phase synchrony when participants maintain the tempo) were coded as 'low disruption' and all other delay conditions were categorized as 'high disruption'. An ANOVA was run on all data except the normal feedback condition with the factors delay condition (high/low disruption), delay type, tempo, and movement type. We focused on the main effect of and interactions with the factor delay category. The effect of delay category was significant, $F(1,23) = 52.51$, $\mathrm{MSE} = 1603.03$, $p < .01$, and did not yield any significant interactions with other factors. Slowing during high disruption conditions ($M = 33.81$ ms) was substantially higher than slowing during low disruption conditions ($M = 0.31$ ms). Thus, the effect of delay phase (synchronous versus asynchronous) has a general effect on disruption that is not modulated by tempo, delay type, or movement type.

2.3. Discussion

Experiment 1 provided strong support for the relative timing hypothesis. Results were strongest for sequence production trials, which conformed to the predicted statistical effects (interaction of tempo and delay for fixed delays, main effect of delay only for adjustable delays). Although results from tapping trials deviated from these statistical predictions, the pattern of results conformed qualitatively to the relative timing hypothesis, and not to the absolute timing hypothesis. This observation was confirmed by an analysis in which delay conditions were categorized according to predicted levels of disruption from the relative timing hypothesis.

Despite this strong support, one could claim that Experiment 1 was not set up optimally to support the absolute timing view. In particular, whereas the absolute timing view predicts maximal disruption around 200–270 ms (cf. Gates et al., 1974; MacKay, 1987), most delays in Experiment 1 were far longer, and only one condition was in the vicinity of this length (the 66% adjustable delay in the 330-ms tempo condition). A better test of the relative timing hypothesis would include a distribution of delay lengths around 270 ms, which is how Experiment 2 was designed.

3. Experiment 2

Experiment 2 was identical to Experiment 1 except that the delays used were shorter (both in the adjustable and fixed delay conditions). Delay lengths and phases in Experiment 2 were designed to form a distribution around lengths that should cause maximal disruption according to the absolute time hypothesis (approximately 200–270 ms), but were also integer multiples of delays used in Experiment 1 in order to facilitate comparisons across experiments. A new sample of participants was selected for Experiment 2 through the same selection criteria used in Experiment 1.

3.1. Method

3.1.1. Participants

Twenty-three new participants from the San Antonio, Texas, community participated in exchange for course credit in introductory psychology (mean age = 19.1, range = 17–26). Twelve participants experienced fixed delays and the rest experienced adjustable delays. Sixteen were female; 7 were male. Three participants were left-handed, the rest were right-handed. Participants reported 2.9 years of experience performing a musical instrument (keyboard or other) or singing (range = 0–15, mode = 0) and 2.2 years of training (range = 0–15, mode = 0) on average. One participant reported 3 years of training and experience on the piano.

3.1.2. Conditions, apparatus, and procedure

The conditions in Experiment 2 were identical to Experiment 1 except for delay conditions, as discussed above. Likewise, the apparatus and procedure were identical to Experiment 1.

3.2. Results and discussion

Analyses of the synchronization phase of each trial verified that participants in Experiment 2 were able to synchronize adequately. IRIs during synchronization deviated from prescribed IRIs by less than 5 ms on average (within 1 SD), and mean asynchronies (time of key press – metronome onset) were within acceptable ranges ($M = -26$ ms for tapping trials, -42 ms for sequencing trials).

Difference scores (mean IRI continuation – mean IRI synchronization) were again used to measure disruption and were analyzed as in Experiment 1. Fig. 2a shows mean difference scores for trials with fixed delays. Results from sequence production trials (left) yielded a main effect of delay, $F(3,33) = 19.43$, MSE = 2780.40, $p < .01$, but no Delay × Tempo interaction. Although this result fits the general predictions of the absolute time hypothesis, it is clear from Fig. 2a that the data do not conform to the prediction that disruption will be maximal for delays within 200–270 ms regardless of tempo. Results from tapping trials (Fig. 2a, right) yielded a main effect of delay, $F(3,33) = 3.86$, MSE = 1455.25, $p < .05$, and a Delay × Tempo interaction, $F(6,66) = 2.88$, MSE = 769.27, $p < .05$, in keeping with the general predictions of the relative time model.

Fig. 2b shows analogous results from trials with adjustable delays. For sequence production trials (Fig. 2b, left), there was a main effect of delay magnitude, $F(3,30) = 9.43$,

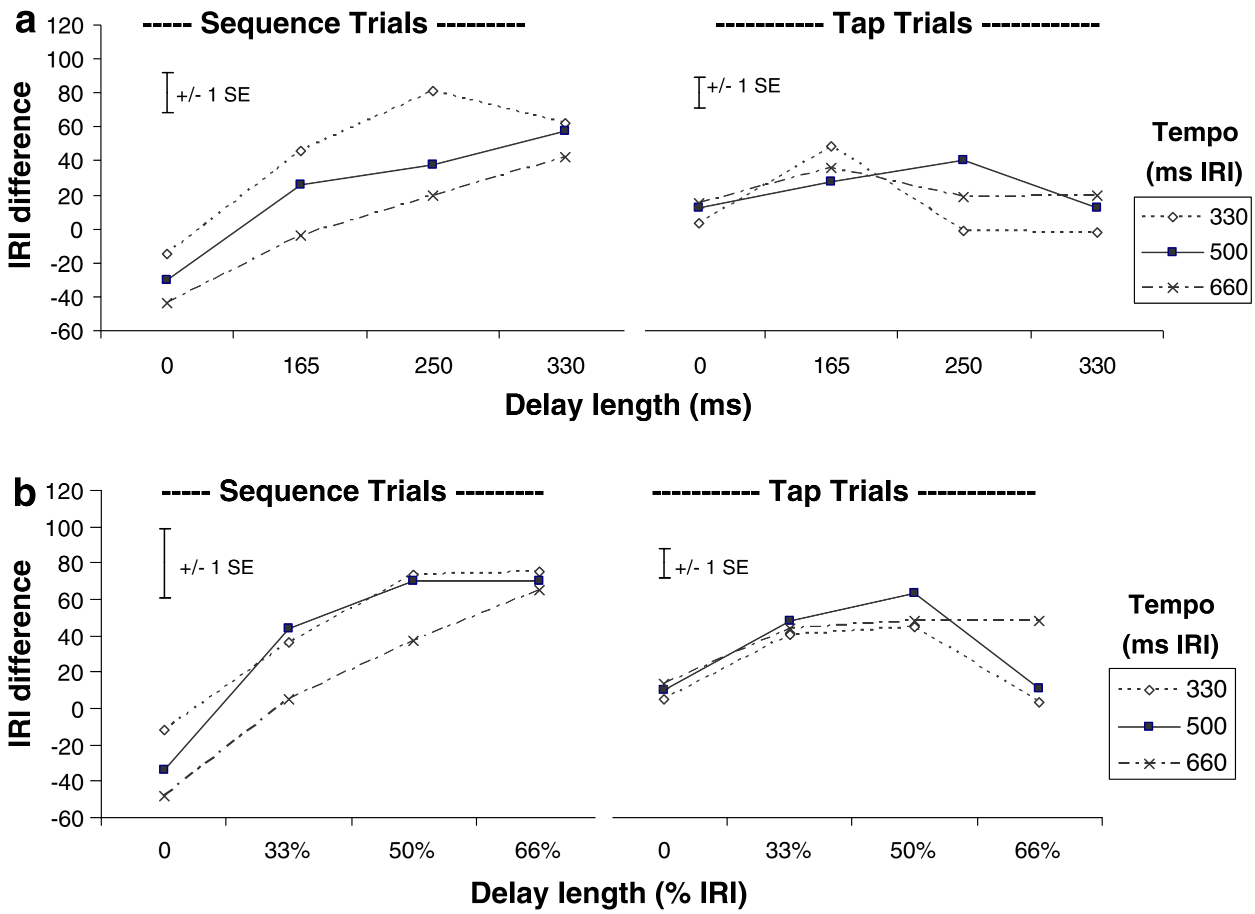

Fig. 2. Experiment 2 differences in mean inter-onset intervals (IRI, continuation–synchronization) as a function of movement type (sequence/tap), prescribed IRI (tempo), and delay magnitude for fixed (a) and adjustable (b) delay types. Error bars represent one standard error of the mean, averaged across conditions.

MSE = 7282.41, $p < .01$, but no Delay × Tempo interaction ($p > .10$), as predicted by the relative time hypothesis. For tapping trials (Fig. 2b, right), there was also a main effect of delay, $F(3,30) = 8.17$, MSE = 1597.68, $p < .01$, but no Delay × Tempo interaction ($p > .10$).

Based on these results, Experiment 2 offers little support for the absolute timing view. Nevertheless, we undertook an analysis to test the qualitative predictions of the absolute time hypothesis as we tested the relative time hypothesis in Experiment 1. For this analysis, delays were categorized as 'high disruption' if they resulted in a delay length between 200 and 300 ms, and as 'low disruption' otherwise. Unlike the analogous analysis from Experiment 1, delay category yielded no significant effect when categories were based on absolute time ($F < 1.00$). This analysis did yield a 3-way interaction among delay category, movement type, and tempo, $F(2,42) = 11.29$, MSE = 838.20, $p < .01$. Post hoc analyses (Tukeys HSD, Fx = .05), however, did not reveal significant differences between any pair of means from different delay categories. Thus Experiment 2, which was designed to provide a framework to support the absolute timing hypothesis, failed to support that hypothesis and added some support for the relative time hypothesis.

Finally, we report an analysis that pooled results across both experiments to examine disruption across a wide range of delays. Fig. 3 displays mean difference scores with feedback conditions plotted according to the relative phase of feedback onsets. For fixed delay conditions, relative phase is the ratio of delay length to the prescribed IRI. When all con-

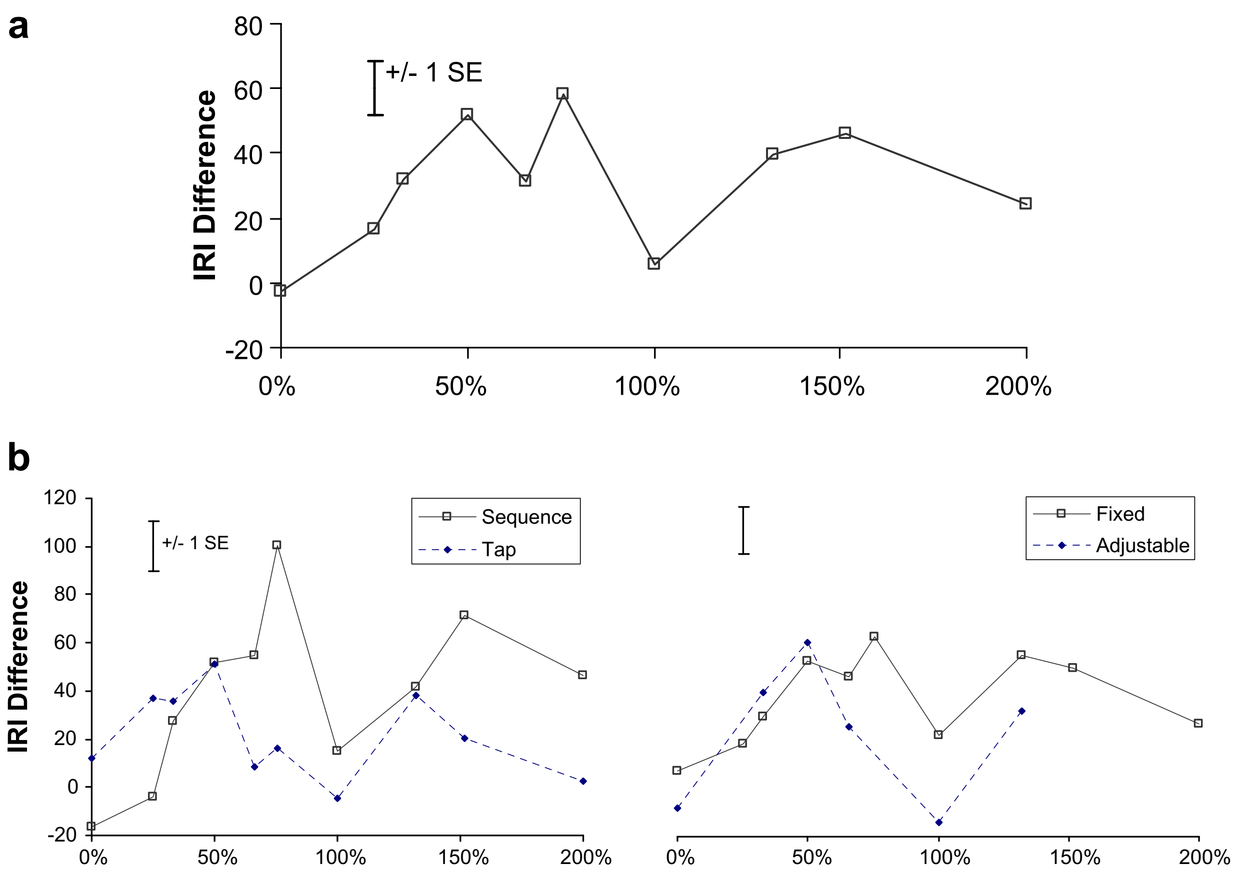

Fig. 3. Difference scores across experiments, plotted according to the relative of feedback onsets within prescribed IRIs (tempo) for all conditions (a), and separately for different movement and delay types (b). Error bars represent one standard error of the mean.

ditions are combined (Fig. 3a), a clear advantage for phase synchrony emerged (i.e., when delays are 0%, 100% or 200% of IRIs). Furthermore, between these minima, the slowing caused by delays varied with relative phase to form inverted U's between points of phase synchrony. The advantage for phase synchrony was not modulated by delay type or by movement type (Fig. 3b), although some subtle differences emerged when comparing these factors. A greater advantage was found for adjustable delays compared with fixed delays (Fig. 3b, right). This result is not surprising considering that adjustable delays are designed to maintain a given phase relationship when global tempo fluctuates. With respect to movement type, the pattern of slowing across relative phase differed (Fig. 3b, left). For tapping trials, slowing increased until 50% relative phase, and then decreased afterwards. By contrast, slowing of sequence production increased for all phase relationships preceding phase synchrony, and then dropped abruptly when phase relationships reached synchrony. The pattern of slowing for sequential trials thus formed a 'sawtooth' pattern rather than the 'seagull' pattern found in tapping trials.

Fig. 4 displays the results of a comparable analysis, in which pooled data were plotted as a function of delay length (which is relative phase × prescribed IRI for adjustable delay conditions). Means across conditions (Fig. 4a) show greater disruption for shorter delays than for longer delays. However, the range of disruptive delays (from 109–436 ms) was broader than in other research that supports the absolute time view. Sensitivity to delay

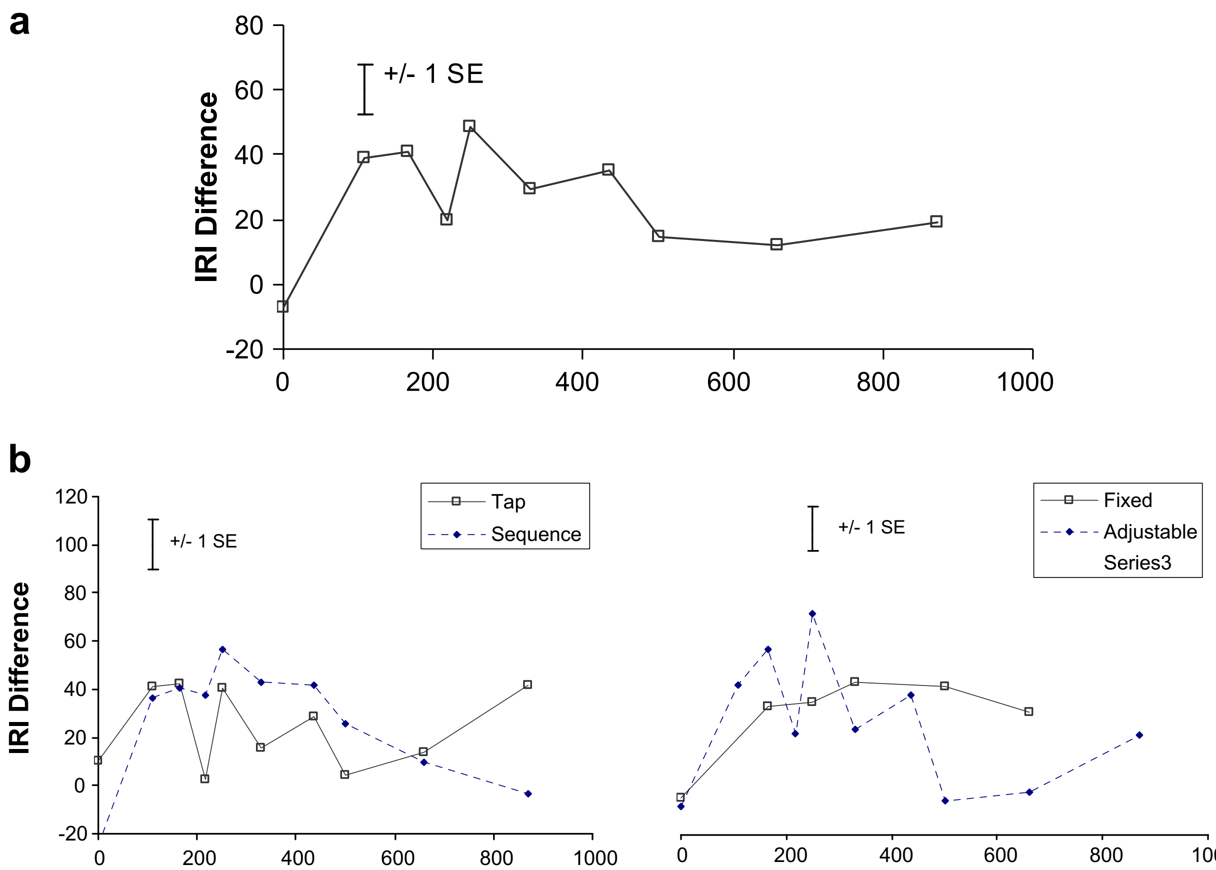

Fig. 4. Difference scores across experiments, plotted according to the length of feedback delays for all conditions (a), and separately for different movement and delay types (b). Error bars represent one standard error of the mean.

length was therefore not as specific as suggested by MacKay (1987). Furthermore, results that were broken down by movement and delay type show the influence of absolute time to be highly qualified. Further investigation verified that only sequence production trials with adjustable delay lengths offer clear support for the absolute time hypothesis. The influence of a delay's absolute time on disruption thus appears to be weaker than the relative position of feedback onsets within recurring IRIs.

4. General discussion

Taken together, these results support the idea that asynchronous feedback disrupts produced timing because of relative timing (i.e., rhythmic) relationships between perception and actions (e.g., Howell et al., 1983), as opposed to the view that disruption occurs when feedback onsets occur after a fixed amount of time (e.g., MacKay, 1987). More generally, relative phase may be a good predictor of the amount of slowing caused by feedback delays. The present results confirm dynamical systems models that incorporate relative phase as an order parameter governing the regulation of perception and action (e.g., Amazeen, Amazeen, & Turvey, 1998; Kelso, 1995; Large & Jones, 1999; Turvey, 1990; cf. Jones, 1976). The role of relative phase was not modulated by delay type, suggesting that sensitivity to phase is not merely the result of participants' attention being drawn to phase when phase is adjustable (i.e., when delay lengths are fixed).

Although short delays on average were more disruptive than long delays this result was highly qualified by movement and delay type unlike the robust effects of relative time. It is possible that absolute time functions to set limits on delays that are potentially disruptive (for a recent review of related research see Repp, 2006). Within these bounds, however, relative time may provide the best account of perception/action coordination. It is not clear at this point why certain experiments have supported the absolute rather than relative timing view (e.g., Butler & Galloway, 1957; MacKay, 1968), though the answer may lie in the difficulty of controlling phase relationships during speech production (which was the task used in those experiments).

We also examined the role of movement in the present study, to explore whether relative phase is related directly to patterns of movement or in a more abstract way to the planning of event onsets. Although we did not record movements, the nature of instructions and evidence from other research suggest that reliably different kinematic patterns were used for the movement tasks. With respect to tapping, instructions emphasized periodic arm movements in which the arm's amplitude is maximal around mid cycle, which is a pattern also found in continuation tapping by Balasubramaniam et al. (2004). Thus, the fact that slowing was maximal when delays were 50% of prescribed IRIs suggests that disruption is maximal when feedback onsets coincide with a change in sign of movement velocity. Movement patterns in music performance are more complex and less well understood. Nevertheless, recent research (and informal observations of performance) suggest that movement amplitude of a single finger is maximal for some time preceding a keypress, and that movement downward toward the key occurs rapidly just before the event onset (Dalla Bella & Palmer, 2004). Moreover, response preparation (both cognitively and motorically) probably begins more than one event prior to the key press (Palmer, 2005; Palmer & Pfordresher, 2003). Thus, disruption of sequence production may be linked to task demands beyond movement amplitude, such as the conflict between the feedback pitch and the pitch being planned for the next event (Pfordresher, 2006).

The present results differ in one salient respect from other results that support relative time accounts of coordination. Unlike results from tasks requiring the coordination of oscillating limb movements (e.g., Schmidt, Shaw, & Turvey, 1993), and the visual perception of coordinated movement (e.g., Bingham, Schmidt, & Zaal, 1999), we found no evidence for stability of antiphase coordination. It could be that antiphase coordination between perception and action is less stable than coordination within one modality (between two limbs or between two perceived events). However, Pfordresher and Palmer (2002) did find some advantage for antiphase coordination in DAF tasks by pianists. It is possible that the mostly unskilled performers in the present tasks were not able to benefit from such alternating rhythms and were instead dependent on phase synchrony (similar to patterns of coordination at fast rates, Kelso, 1995).

The fact that slowing was minimal for delays that were 100% and 200% of IRIs may seem odd for sequence production conditions, given that auditory feedback presented pitches from preceding events. Indeed, much recent evidence suggests that hearing pitches intended for previous (or future) positions in auditory feedback that is synchronized with movements (much like the present 100% and 200% phase shifts) can disrupt production (Pfordresher, 2003, 2005; Pfordresher & Palmer, 2006). Such disruption, however, is limited to error rates, whereas timing in such conditions is relatively unhindered (Pfordresher, 2003). Errors were in fact slightly higher for conditions in which auditory feedback was roughly synchronous but presented past pitches. These results were not significant, however, probably due to the fact that feedback in the present experiments was more often asynchronous than synchronous given the nature of the manipulations (see Pfordresher, 2006; for further discussion).

In conclusion, the current results offer significant support for the view that perception and action are coordinated with respect to relative timing, and that the control of timing may be disrupted (e.g., slowed) when such rhythmic relationships are perturbed. These results held in general for simple tapping and for more complex musical sequence production. Subtle differences between movement conditions, at the same time, suggested that coordination is based on more physical properties of movement for tapping tasks, and on higher-level planning processes for complex sequence production.

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