

The Dynamics of Disruption From Altered Auditory Feedback: Further Evidence for a Dissociation of Sequencing and Timing

Peter Q. Pfordresher and J. D. Kulpa
University at Buffalo, the State University of New York

Three experiments were designed to test whether perception and action are coordinated in a way that distinguishes sequencing from timing (Pfordresher, 2003). Each experiment incorporated a trial design in which altered auditory feedback (AAF) was presented for varying lengths of time and then withdrawn. Experiments 1 and 2 included AAF that resulted in action-effect asynchronies (delayed auditory feedback) during simple tapping (Experiment 1) and melody production (Experiment 2). Asynchronous AAF immediately slowed production; this effect then diminished rapidly after removal of AAF. By contrast, sequential alterations of feedback pitch during melody production (Experiment 3) had an effect that varied over successive presentations of AAF (by increasing error rates) that lasted after its withdrawal. The presence of auditory feedback after withdrawal of asynchronous AAF (Experiments 1 and 2) led to overcompensation of timing, whereas the presence of auditory feedback did not influence performance after withdrawal of AAF in Experiment 3. Based on these results, we suggest that asynchronous AAF perturbs the phase of an internal timekeeper, whereas alterations to feedback pitch over time degrade the internal representation of sequence structure.

Keywords: altered auditory feedback, delayed auditory feedback, sequencing, timing, sensorimotor adaptation

When one produces a complex action sequence, such as playing a melody or speaking, the planning and production of actions run concurrently with the perception of the outcomes of those actions. Our research addresses this link in the context of auditory-motor associations in music performance. In music, as in speech, the auditory pattern one produces is critical for the purpose of communication. Interestingly, existing research suggests that fluent performance does not rely on the presence of auditory outcomes. For instance, the absence of feedback appears to have little influence on production of musical keyboard sequences (Finney, 1997; Finney & Palmer, 2003; Pfordresher, 2005; Repp, 1999). However, fluent performance does appear to rely on congruity between production and perception, evidenced by the disruptive effect of altered auditory feedback (AAF).

The debilitating effects of *delayed auditory feedback* (DAF), a form of AAF, on production are well-established. DAF involves adding a constant lag between the time of an action and the time of the associated auditory event; DAF typically leads to asynchro-

nies between actions and feedback. The effects of DAF were first observed in speech (Black, 1951; Lee, 1950) and were later demonstrated in music performance across a variety of instruments (Havlicek, 1968). Its effects include slowing of production (e.g., Gates, Bradshaw, & Nettleton, 1974; Howell, Powell, & Khan, 1983), increases in error rates (e.g., Fairbanks & Guttman, 1958), and increased variability of produced timing (e.g., Howell & Sackin, 2002; Pfordresher & Palmer, 2002). Disruption varies with length of delay. In general, the most disruptive delays lag behind produced actions by about 200 ms (MacKay, 1987), though it is likely that disruptive effects are based on relative timing between actions and sounds rather than absolute time (Finney & Warren, 2002; Pfordresher & Benitez, 2007; Robinson, 1972).

The multiple forms of disruption that DAF causes may reflect differences in the temporal coordination between actions and auditory feedback that can arise in common DAF tasks (see Pfordresher, 2006, for further discussion). Consider the experience of DAF with a lag of 200 ms while performing a rhythmically variable keyboard sequence. When the performer's inter-response intervals (IRIs) are longer than 200 ms, feedback events (from DAF) would sound between the keypress associated with that event, yet before the next keypress. We refer to this kind of perception/action coordination as *asynchronous* with respect to onset timing, yet normal with respect to feedback *contents* in that the expected pitch follows each action. However, for IRIs that are equivalent to 200 ms, feedback onsets would be synchronized with the subsequent keypress, leading to synchronized feedback that is altered with respect to pitch contents. Finally, if IRIs are shorter than 200 ms, feedback would be both asynchronous and altered with respect to contents, because feedback onsets from one event would sound after the subsequent keypress. When the timing of

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Peter Q. Pfordresher and J. D. Kulpa, Department of Psychology, University at Buffalo, the State University of New York.

J. D. Kulpa is now at the Department of Psychology, New Mexico State University.

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Correspondence concerning this article should be addressed to Peter Q. Pfordresher, Department of Psychology, 355 Park Hall, University at Buffalo, Buffalo, NY 14260. E-mail: pqp@buffalo.edu

feedback is controlled such that feedback events are asynchronous with actions but are not altered in content (i.e., feedback contents meet expectations associated with the most recent produced action), their effects are more limited to timing of IRI, with minimal effects on accuracy (Pfordresher, 2003). In fact, based on results in which the effect of DAF is unchanged when feedback contents are altered, Howell and colleagues have argued that feedback only influences the timing of action via rhythmic relationships between perception and action (Howell & Archer, 1984; Howell et al., 1983; cf. Howell, 2001). However, other evidence suggests that AAF may cause disruption even when it is synchronized with actions (unlike what is commonly true of DAF). Disruptions based on alterations of contents alone (i.e., for synchronous feedback) suggest a locus of disruption at the level of event planning (cf. Hommel, Müsseler, Aschersleben, & Prinz, 2001).

Although asynchronous feedback can be highly disruptive to timing, alterations of feedback contents tend to disrupt accuracy instead. Specifically, a kind of pitch alteration, referred to here as a *serial shift* of feedback pitch, disrupts production primarily by increasing error rates (Pfordresher, 2003; 2005; 2008; Pfordresher & Palmer, 2006). During serially shifted feedback, the depression of a piano key triggers the presentation of a pitch associated with a different serial position, either from the past or future, at a constant lag or lead. For instance, the lag-1 serial shift (which is used here) results in the generation of pitches from the most recent serial position (i.e., one always hears the pitch associated with the previous keypress). Critically, serially shifted feedback is always synchronized with keypresses (given standard equipment-related lags, such as the unnoticeable lag present in MIDI devices). Because serial shifts do not influence the synchronization of actions with perceived events, their effects suggest a different source of disruption, namely the serial retrieval of events from memory (cf. Palmer & Pfordresher, 2003; Pfordresher, 2006; Pfordresher, Palmer, & Jungers, 2007). Other alterations of feedback contents have less consistent effects. For instance, altering the pitch contents of auditory feedback during piano performances such that feedback pitches are selected at random (Finney, 1997; Pfordresher, 2005) or simply transposing feedback pitches (Pfordresher, 2008) does not disrupt production of keyboard sequences.

A Shared Representation for Perception and Action: Sequencing Versus Timing

Differences between the effects of asynchronous versus serially shifted feedback led Pfordresher (2003, 2006) to propose a hierarchical model of perception/action coordination based on different time scales. Based on a long-standing distinction between sequencing and timing (e.g., Krampe, Mayer, & Kliegel, 2005; MacKay, 1987; Palmer, 1997), this model separates the timing (onset synchrony) and sequencing (serial order) of planned actions and their consequences. Figure 1 shows a schematic version of this model. The higher time scale, sequencing, represents the activation of sequential events (A4–D4) as one proceeds through the sequence (shown as bar graphs). For production, the event with the highest activation is selected via memory retrieval for production at the appropriate time (as determined by the lower time scale). For perception, activations represent the most likely perceived event category (i.e., perceived pitch). The lower time scale represents fluctuations in activation across time associated with planned and anticipated event onsets, independent of event contents. In Figure 1 these fluctuations are shown as oscillations (cf. Large & Jones, 1999; McAuley, 1995), although we are at present not concerned with differentiating such approaches from other models of internal timekeeping based on stochastic clock-counters (e.g., Mates, 1994; Vorberg & Wing, 1996; Wing & Kristofferson, 1973). Critical to the current research is the assumption that sequencing draws on serial retrieval mechanisms, whereas timing involves more basic timekeeping mechanisms. Similarly, Krampe and colleagues (2005) claimed that the organization of sequencing (in their study, sequencing referred to ordering of durations in a rhythmic pattern) is regulated by executive control processes whereas timing is not.

How does this distinction between sequencing and timing relate to auditory feedback? The performer is thought to be sensitive to different aspects of the way in which perception and action are coordinated. When auditory feedback fails to align with planned actions, either with respect to serial position (sequencing) or onset timing, the alteration of feedback disrupts the underlying representation of sequence structure in that same way. For instance,

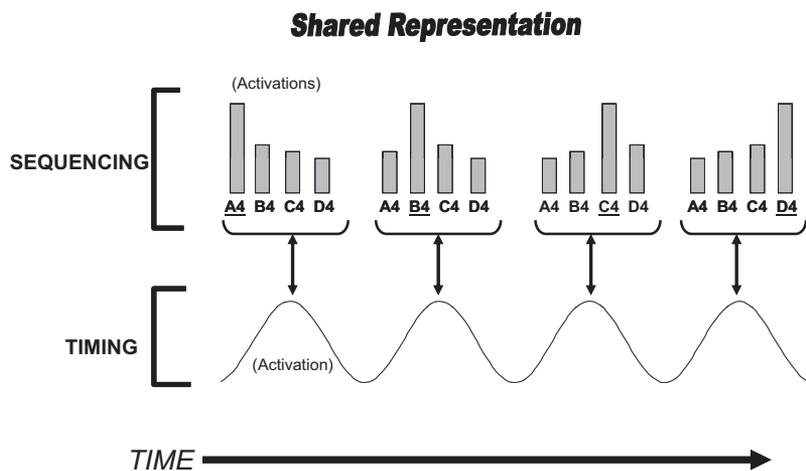


Figure 1. Proposed framework for a representation of sequence structure that is shared across the domains of perception and action.

when perceived events fail to synchronize with actions, yet still match the intended outcomes of actions with respect to content, such mismatches are thought to disrupt selectively the event representation at the level of onset timing, while leaving sequencing unperturbed. By contrast, when the sequential organization of auditory feedback conflicts with planned sequential structure, but is synchronized with actions, the manipulation is thought to perturb only the representation of sequencing, and not timing. In the past, this assumption has been supported by the aforementioned dissociation between effects on timing (by asynchronies) versus accuracy (by serial shifts).

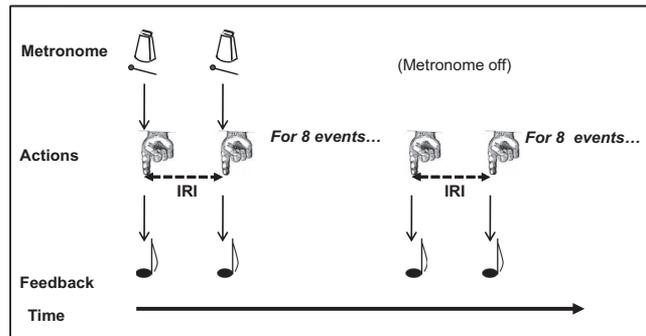
The Dynamics of Disruption to Sequencing and Timing

In this paper we address the temporal dynamics of disruption from AAF in a paradigm that involves altering auditory feedback for varying amounts of time and then withdrawing AAF in each trial. This paradigm is illustrated in Figure 2. At the beginning of the trial, participants produce a sequence with normal feedback during segment 1, followed immediately by a second segment in which auditory feedback from actions is altered for different lengths of time (in different trials), and finally a third segment in which AAF is removed. We address whether disruptive effects accumulate over time during segment 2 and whether they persist after AAF is removed in segment 3. During segment 3, feedback could either return to normal or be removed entirely. The hierarchical approach described above predicts that disruption of production at different time scales will lead to different patterns of disruption and recovery across segments 2 and 3. Furthermore, we test the influence of feedback presence on the way in which people recover from AAF during segment 3.

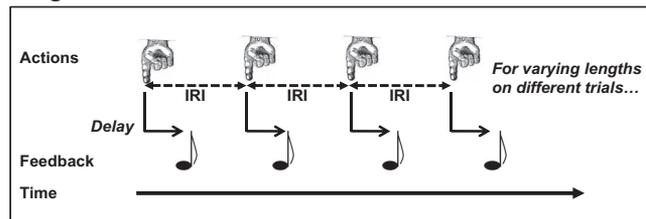
Internal timekeeping, which is thought to be disrupted by asynchronous AAF, is typically assumed to be guided by two parameters: phase and period. (e.g., Large & Jones, 1999; Mates, 1994; McAuley, 1995; Vorberg & Wing, 1996). Phase refers to the positioning of onset times determined by the internal timekeeper (shown as activation peaks in Figure 1). Phase synchrony occurs when timekeeper onsets coincide with event onsets in an external pattern (e.g., a metronome) to which the timekeeper synchronizes. Period refers to the time interval elapsing between timekeeper onsets. Period synchrony refers to whether these intervals match the elapsed time between event onsets in the external pattern. When the internal timekeeper synchronizes with external events, it can adapt its phase and/or period to do so. The degree to which timekeeping relies on phase versus period adaptation can lead to dramatic changes in the way in which a system maintains synchrony (McAuley & Jones, 2003).

We predicted that the effect of asynchronous feedback would be attributable to disruption of phase rather than period of the internal timekeeper. That is, asynchronous AAF slows production by persistently perturbing the relative phase of auditory feedback onsets relative to planned onsets associated with production, leading to a succession of phase shifts that in practice lengthen IRIs. However, lengthening of IRIs seen during asynchronous AAF would therefore not be attributable to a distortion of the period of the internal timekeeper (i.e., the system would not “lose track” of the target time interval). This prediction is associated with two critical results. First, phase adaptation is immediate and is typically ob-

Segment 1: “Baseline”



Segment 2: “AAF”



Segment 3: “Recovery” (feedback absent)

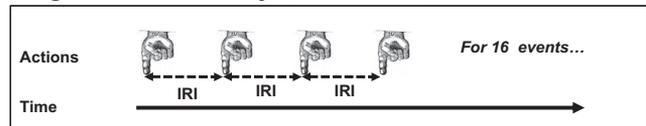


Figure 2. Illustration of trial structure, using a representative trial from Experiment 1 (with feedback absent from segment 3) as an example. Metronome onset times are represented as cowbells, produced action onset (taps) are shown as downward pointing fingers, and feedback onsets are shown as musical notes. Interresponse intervals (IRIs) are measured based on actions, as shown. This figure also illustrates slowing of IRIs in segment 2 and return to baseline (segment 1) rates in segment 3 when feedback is absent. See text for details regarding other trial types and experiments. Note that the three segments follow each other directly without a pause during trials.

served after the first perturbation, in contrast to period adaptation (Large, Fink, & Kelso, 2002). Second, the effect of asynchronous feedback should dissipate rapidly after the removal of the alteration (e.g., Flach, 2005; Repp, 2000, 2001a, 2002, 2003). A similar prediction emerges from the model of Howell (2001), who suggested that slowing of timing by DAF can be modeled by adding a constant (proportional to the delay) to the timekeeper period, but only while DAF is present (i.e., the effect should not persist).

We based this prediction on research concerning the effect of perturbations to the timing of metronome tones during synchronization, which suggests that period adaptation only occurs in limited circumstances (Repp, 2001a, 2001b; Repp & Keller, 2004). Furthermore, qualitative results based on phase perturbation are similar to results from earlier research on adaptation effects to DAF in speech production tasks (see Yates, 1963, pp. 219–220 for a review), and the effects of DAF on birdsong are likewise transitory (Cynx & von Rand, 2001).

Sequential retrieval, which is thought to be disrupted by serially shifted AAF, is associated with a longer time course than is the

disruption of timing. Earlier analyses of the effects of serially shifted AAF on patterns of serial ordering errors (which are commonly used to measure event accessibility during retrieval) suggested that serial shifts may reduce distinctiveness among events in memory (Pfordresher & Palmer, 2006). With respect to the current design, we predicted that serially shifted AAF may gradually weaken the strength of connections between serial positions in the performance and contents associated with those positions. Based on this assumption, we predicted that the effect of serial shifts would accumulate with repeated exposure to AAF and should persist after AAF is removed. Furthermore, we anticipated that elevations in error rates caused by serial shifts should vary with metrical position in the produced sequence, given that metrical representations facilitate the retrieval of musical sequences (Pfordresher et al., 2007).

In addition to manipulating the length of time over which participants experienced AAF, we also manipulated whether or not feedback was present after the withdrawal of AAF. That is, participants could either experience a transition from altered to normal feedback or a transition from altered to absent feedback. We used this manipulation to test whether normal feedback, which does not appear to be necessary for fluent performance, may help the performer to recover from the effects of AAF. Such a result would be consistent with earlier accounts of the effect of AAF that were based on the idea that production is guided by a feedback control mechanism (e.g., Wiener, 1948). In this context, the presence of normal feedback, as opposed to absent feedback, may act as a "corrective" rather than "error" signal.

Current Experiments

We report three experiments that addressed the temporal dynamics of disruption of rhythmic tapping (Experiment 1) and melodic sequence production (Experiments 2 and 3), by asynchronous feedback (Experiments 1 and 2) or serial shifts of feedback pitch (Experiment 3). Each experiment incorporated the three-segment trial structure described above, in which feedback alterations would appear for varying lengths of time in segment 2 and then be removed in segment 3, when auditory feedback would either cease or return to normal. The major purpose of this research was to test whether disruption from different kinds of feedback manipulations (asynchronous versus serial shift) exhibit different temporal dynamics. To the extent that they do, the hierarchical model described above would be supported. Furthermore, we are interested in the temporal dynamics of disruption within each segment, as described above.

Experiment 1

Experiment 1 incorporated a simple isochronous tapping task with asynchronous AAF, selectively incorporated during segment 2 of experimental trials. Specifically, feedback from a varying number of finger taps could be delayed in segment 2, and this sequence of delayed feedback events was immediately followed by segment 3, in which feedback would either return to synchrony or cease altogether. In addition, control trials were randomly intermingled that included 16 segment 2 events with normal feedback. We focused on slowing of IRIs by asynchronous AAF given the reliability of this effect in similar conditions found in other re-

search (Pfordresher, 2003; Pfordresher & Benitez, 2006). As stated earlier, we predicted that asynchronous AAF disrupts phase, but not period, of an internal timekeeper. Thus, the effect of the asynchrony should appear as soon as the asynchrony is introduced, should not evolve across multiple delays, and should vanish as soon as alterations are removed.

Method

Participants

Thirty-three individuals (mean age = 19.7, range 18-28, seven declined to report age) volunteered to participate in exchange for course credit in introductory psychology at the University at Buffalo, State University of New York (UB). Eight of these were female and nineteen were male (six declined to report gender). Twenty-six were right-handed and one was left-handed (six declined to report handedness). All participants reported no hearing impairment and no motor impairment of the right hand. Fifteen participants (45%) reported musical training on an instrument or voice of at least one year in duration (range 1-36, mode across all participants = 0)¹. Five participants reported training on the piano; however, only one participant had more than a year of private lessons (12 years) and did not report playing the piano currently. Thus on the whole this sample represents a musically untrained group. One participant reported having absolute pitch.

Conditions

Each trial was divided into three segments. Segment 1 functioned as a within-trial baseline and included a synchronization phase of eight events (with a metronome period of 500 ms), followed by an eight-event continuation phase with normal (synchronous) feedback with a fixed feedback pitch of C4. In experimental trials, segment 2 included asynchronous AAF, and could vary in length to last for 1, 2, 4, 8, or 16 taps. Asynchronous feedback events in segment 2 were 50% of each anticipated inter-response interval, based on a running average of previous IRIs². An additional set of control trials substituted delayed feedback events with a series of 16 taps with normal feedback. Finally, segment 3 allowed us to examine recovery from asynchronous feedback and included 16 events for which feedback was either normal (synchronous) or absent. For the first 16 subjects, the end of the trial was signaled by either a single note (when feedback was absent during segment 3) or the cessation of feedback (when present in segment 3). However, some participants found this confusing, which led to a few trials with long pauses at the beginning of segment 3 when feedback was removed (these

¹ Total years of experience was computed by summing years of experience across all instruments reported, rather than total years of experience for any instrument. Thus, years of musical experience can in principle be greater than a participant's age. The participant reporting 36 years of experience, for instance, reported 16, 10, and 10 years of experience on three different instruments, respectively.

² The experiment also included conditions with 2% and 75% that are excluded now for the sake of brevity. The 2% condition led to negligible effects and a computer error complicated the interpretation of the 75% delay.

pauses, which were over a second in length, were removed from data analyses). Thus, for the remaining 17 participants, the end of each trial was signaled by three feedback pitches on an additional three taps (not included in analyses) that formed a triad (G3–E4–C4). No differences between these groups of participants were evident (after removing pauses from the first group of participants) and so both groups are aggregated in the analyses reported here.

A total of 10 experimental trials were created by crossing the variables segment 2 length (five levels) with segment-3 feedback presence (two levels). Two normal feedback control trials were also included, one with feedback during segment 3, the other without. Each trial type was repeated twice, in the first and second halves of the experimental session.

Apparatus

Participants used a Roland SPD-6 percussion pad for tapping responses, which was supported by a drum stand positioned at a comfortable height. 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.

Procedure

At the beginning of the session, participants were trained to synchronize with the metronome and were familiarized with the experience of asynchronous AAF. Participants were instructed to tap by rotating at the elbow and to tap with their right index finger; this tapping regime was found to provide the most consistent responses from the drum pad and helped avoid fatigue for the participants. Following this familiarization phase the experimenter described the task structure and administered a practice trial that included asynchronous feedback in segment 2 and absent feedback in segment 3. Participants were told to try to maintain the metronomic tempo throughout the trial and to keep tapping until the end of the trial was signaled (see Conditions). Participants then completed all experimental trials, followed by questionnaires regarding their musical background, demographic information, and hearing sensitivity.

Data Analysis

We focus on the average timing of IRIs—the time from the onset of one keypress to the next. In order to show how the addition and withdrawal of AAF influenced IRIs, we computed difference scores—called IRI-diff—between trial segments. IRI-diff scores for segment 2, which contrast segments 2 and 1, measure the disruptive effect caused by AAF when AAF is present. IRI-diff scores for segment 3, which contrast segments 3 and 1, measure recovery from AAF after AAF is withdrawn. Positive IRI-diff scores indicate slow IRIs relative to segment 1 and negative IRI-diff scores indicate fast IRIs relative to segment 1.

Results

Analyses of IRI-diff scores were planned according to the hierarchical structure of trials. We first analyze changes in IRI-diff as a function of trial segment, followed by analyses of data within segments 2 and 3. For segment 2 we focus on the single factor, number of delayed events (1, 2, 4, 8, or 16). For segment 3 we focus on two factors, number of delayed events in the preceding segment (2) as well as feedback presence (present/absent) within segment 3. For each analysis, we report within-participants analyses of variance (ANOVA) for that design. When relevant we also report one-sample *t*-tests that contrast cell means with the expected value based on the null hypothesis, which is IRI-diff = 0. For analyses of segment 2, *t*-tests are one-tailed given that only an increase is predicted; whereas for analyses of segment 3, *t*-tests are two-tailed (any comparable analyses of control trials are two-tailed). Following these analyses of mean IRI-diff within each segment, we report analyses that address the dynamics of disruption within each segment by examining the time series of mean IRIs. In order to address possible contributions of musical training, all analyses reported below were also conducted with the additional factor, musical training, with the musician group comprising those participants who reported at least one year of music lessons. No effects of musical training emerged from these analyses and so we only report analyses that are averaged across all participants.

Analyses of control trials (in which the two trials with a 16-event AAF segment were replaced with normal feedback for that segment) yielded no significant changes in IRIs across segments or across events within segments (M IRI-diff for segment 2 = -5.3 , for segment 3 = -5.9). Thus we will not consider these trials further.

Within-Segment Means

Figure 3 shows IRI-diff scores from Experiment 1. Means within segments 2 and 3 are shown in Figure 3A. IRIs slowed in segment 2 while delays were present but then recovered in segment 3 when delays were removed. This difference was reflected in a significant difference between segments 2 and 3, $t(32) = 6.44$, $p < .01$. Furthermore, mean IRI-diff in segment 2 significantly exceeded zero, $t(32) = 4.71$, $p < .01$, but the mean for segment 3 did not differ significantly from zero.

The effect of segment 2 length (the number of delayed events) on IRI-diff scores within segment 2 is shown in Figure 3B. The effect of length was not significant ($p > .10$) and each condition's mean was significantly greater than zero [$t(32) > 2.20$, $p < .05$ for each, one-tailed]. Thus it appears that the effect of asynchronous feedback did not evolve over time while the alterations were present.

Results from segment 3, shown in Figure 3C, address the degree to which participants recovered from the effect of asynchronous feedback after asynchronies were removed. In principle, the degree of recovery could be influenced by the number of delays one had experienced in segment 2 despite the fact that length did not influence behavior within segment 2. The ANOVA on the factors segment 2 length and feedback presence yielded a significant main effect of segment 2 length, $F(4, 128) = 5.16$, $MSE = 810.62$, $p <$

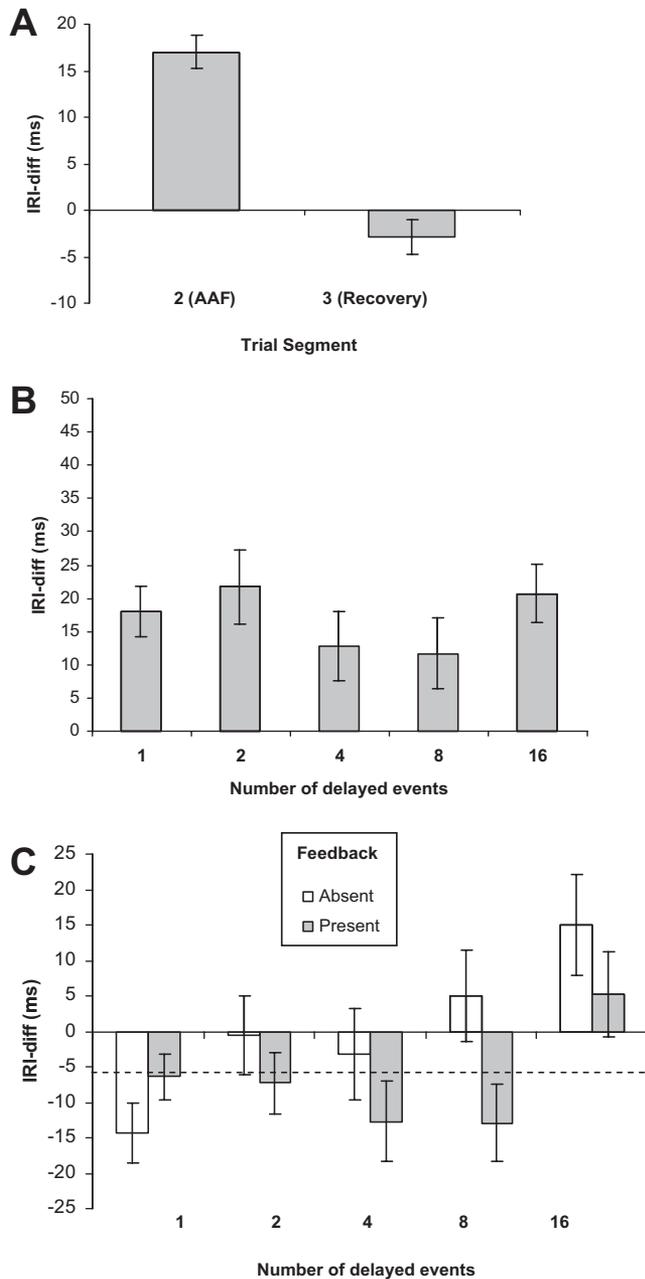


Figure 3. Segment means from Experiment 1; error bars represent one standard error of the mean (between participants). A: Mean IRI-diff scores for different trial segments in Experiment 1 across all conditions. B: Mean IRI-diff scores for segment 2 (AAF) by segment 2 length (# of events). C: Mean IRI-diff scores for segment 3 (recovery) by segment 2 length and feedback presence within segment 3; the dashed line represents the mean IRI-diff scores for segment 3 in control trials.

.01, $\eta_p^2 = 0.16$,³ and a marginally significant interaction ($p = .06$, $\eta_p^2 = 0.07$) but no main effect of feedback presence ($p > .10$, $\eta_p^2 = 0.07$). It is worth noting, however, that IRI-diff scores overall were negative by more than two standard errors when feedback was present ($M = -6.83$, $SE = -3.00$) but were close to zero when feedback was absent ($M = 0.39$, $SE = 2.78$). The main effect of

segment 2 length reflects the fact that IRI-diff scores following segment 2 were generally negative for segment 2 lengths of 1, 2, 4 or 8 events but were positive for length 16. This change in recovery with segment 2 length was more linear when feedback was absent than when feedback was present, accounting for the marginal interaction of segment 2 length with feedback presence.

The data from Figure 3C may be taken to indicate that performance with 16 asynchronies in segment 2 did not change when AAF was removed, that performance did not “recover.” This was not the case, however. A follow-up analysis on the 16-delay condition showed that IRI-diff scores were considerably higher in segment 2 ($M = 20.68$, $SE = 4.36$) than in segment 3 ($M = 9.58$, $SE = 4.76$), $t(32) = 2.57$, $p < .05$. Thus it is fairer to say that performance did recover in the 16-delay condition but that recovery was not complete.

Time Series Analyses

Results thus far are generally consistent with the idea that asynchronous feedback generates persistent phase perturbations of an internal timekeeper, and as such its effects are rapid yet transient. However, there may be trends within each segment that are masked by the within-segment averages reported above. Thus we also analyzed IRI time series across segments 2 and 3. Figure 4 shows the mean data for each combination of segment 2 length (shown in different panels) and feedback presence during segment 3 (series within each plot). Each time series begins on the penultimate event of segment 1 to illustrate change in timing with the introduction of asynchronous feedback.

As can be seen, the effect of asynchronous feedback in segment 2 was apparent on the first event of that segment (position 17). There was a tendency for the IRI associated with the first delayed event to be somewhat longer than IRIs following subsequent delays. Other than this, there was no tendency for IRIs to change across successive delays.

A more complex pattern of change in IRIs was observed within segment 3. In general, IRIs reached an asymptotic level within 2–3 feedback events. However, in some cases asymptotic performance appeared to be faster than performance during segment 1 (e.g., four delays followed by normal feedback, Figure 4C), and sometimes there appeared to be a pattern of overcompensation followed by return to segment 1 IRIs (e.g., eight delays followed by normal feedback, Figure 4D). One possibility that emerges from visual examination of Figure 4 is that the some differences in segment 3 observed in Figure 3C may be due to differences in *relaxation time*, the time it takes performance to reach asymptotic level, rather than the asymptote itself (cf. Large et al., 2002). Thus we performed a set of analyses designed to separate relaxation time from asymptotic performance.

Our approach involved fitting an exponential decay function to the data from segment 3, starting with the final event from segment 2. A similar approach was used by Large and colleagues (2002); however we use a simpler function in which slope and intercept contribute additively in the context of an exponential decay:

³ Significant effects were confirmed using Greenhouse-Geisser correction.

$$IRI-diff_n = \alpha + 2 \times [1 - (1 + \exp(-\beta n))^{-1}] \times (IRI-diff_0 - \alpha) \quad (1)$$

Where β determines the slope of the exponential decay to an asymptote, α , and n refers to serial position within segment 3 (starting at $n = 1$). This decay function is further constrained so that the initial data point is equal to the final IRI of segment 2 ($IRI-diff_0$) and all values range between this value and the asymptote (the difference between $IRI-diff_0$ and α).

We fit this function to the data shown in Figure 4 after converting to IRI-diff scores (contrasting with segment 1), starting with the last IRI of segment 2 in each condition. Best-fitting parameter values, and variance accounted for (VAF) are shown in Table 1 for all combinations of segment 2 length and feedback presence. We entered IRI differences into this function and this is the measurement scale reflected in Table 1 values. Fits were generally good, (lowest VAF = 55%, M VAF = 82%), which suggests that Equation 1 provides an adequate description of relaxation behavior in this task.

Asymptote parameters test whether mean IRI-diff scores shown in Figure 3 are merely a byproduct of relaxation time. As can be seen, Table 1 values generally confirm IRI-diff scores. Asymptotes scaled linearly with segment 2 length when feedback was absent, and were negative for length 1 (-3.27) and positive for length 16 (10.97). By contrast, asymptotes were generally negative when feedback was present and were only slightly positive for length 16.

Parameters for relaxation time provide additional information about how quickly participants recovered (to the extent that they did) from DAF. Relaxation times were faster (higher in value) when segment 2 was shorter and when feedback was present. Thus, although segment 2 length did not influence IRI increase while asynchronous feedback was present, it did influence how quickly participants returned to an asymptotic level of performance once asynchronous feedback ended.

Discussion

In general, the results of Experiment 1 support the idea that asynchronous feedback disrupts timing by imposing a succession of phase perturbations on performance, but does not necessarily change the period of an internal timekeeper. The effect of asynchronous feedback was seen immediately, did not change with successive asynchronies, and in most conditions disappeared rapidly upon removal. Because asynchronies are persistent across events and consistent in magnitude, the effect of their phase perturbations when AAF is present is that of a similarly persistent and consistent change in IRI timing.

Although most conditions demonstrated recovery during segment 3, longer runs of feedback delays (16 events) diminished the return of IRIs to the original tempo. This was particularly true when the recovery segment of the trial did not include auditory feedback. In this condition, behavior does not seem to reflect an exclusive role of phase perturbations and may reflect a combination of phase and period adaptation (Repp, 2001b) perhaps resulting from the participant “losing track” of the period (McAuley, 1995).

Responses to feedback presence after AAF withdrawal (segment 3 of trials) suggest overcorrection in the presence of normal

feedback, but not when feedback was absent. This result is analogous to patterns of speeding up that occur in synchronization tasks when sounds of a metronome (without auditory feedback) are converted to auditory feedback without the participant’s knowledge (Fraisse & Voillaume, 1971; cited in Repp & Knoblich, 2007). These “pseudo-synchronization” effects are usually interpreted as following from the fact that people do not interpret metronome sounds as resulting from their actions (but see Flach, 2005).

Experiment 1 incorporated a simple isochronous tapping task. Though this kind of task is easy to learn and can yield highly reliable timing data, it is limited in scope. Most important, it is possible that the simple task of maintaining phase and period, without having to remember and reproduce a sequence of actions, may lead to simplistic behavioral effects, and perhaps the dominance of phase perturbation in the data of Experiment 1 are a byproduct of this simplicity. Thus, in Experiment 2, we tested whether results would generalize to the production of melodic sequences.

Experiment 2

The major goal of Experiment 2 was to generalize the tapping task of Experiment 1 to a more complex sequence production task. Participants in Experiment 2 performed an 8-note melody on a piano keyboard. Trials were otherwise identical to Experiment 1.

Method

Participants

Twenty-three students from UB (mean age = 20.4, range 18–32) volunteered to participate in exchange for course credit in introductory psychology. Five of these were female and 18 were male. Twenty-two were right-handed and one was left-handed (six declined to report handedness). No participants reported hearing impairment or motor impairment of the right hand. Sixteen participants (70%) reported a year or more of musical training or training in singing. Mean years of training among these participants was 7 years (range 1–17, mode across participants = 0). Six participants reported training on the piano; however, only one participant had more than a year of private lessons (7 years) and did not report playing the piano currently. No participants reported having absolute pitch.

Because of the close relationship between Experiments 1 and 2, we compared levels of musical training across both experiments, both with respect to reported years of training across all participants (including those with no training) and for those reporting at least one year of training. Samples in each experiment did not differ reliably with respect to total years of training across all instruments, or years of training in the piano (two sample t -tests, $\alpha = .05$). The difference across Experiments 1 and 2 in the percentage of participants reporting some musical training approached significance [$\chi^2(2) = 5.29$, critical $\chi^2 = 5.99$ at $\alpha = .05$], with marginally more musicians in Experiment 2 than in Experiment 1.

Materials, Conditions, and Apparatus

The structure of trials and manipulation of auditory feedback was identical to Experiment 1. Likewise the apparatus for Exper-

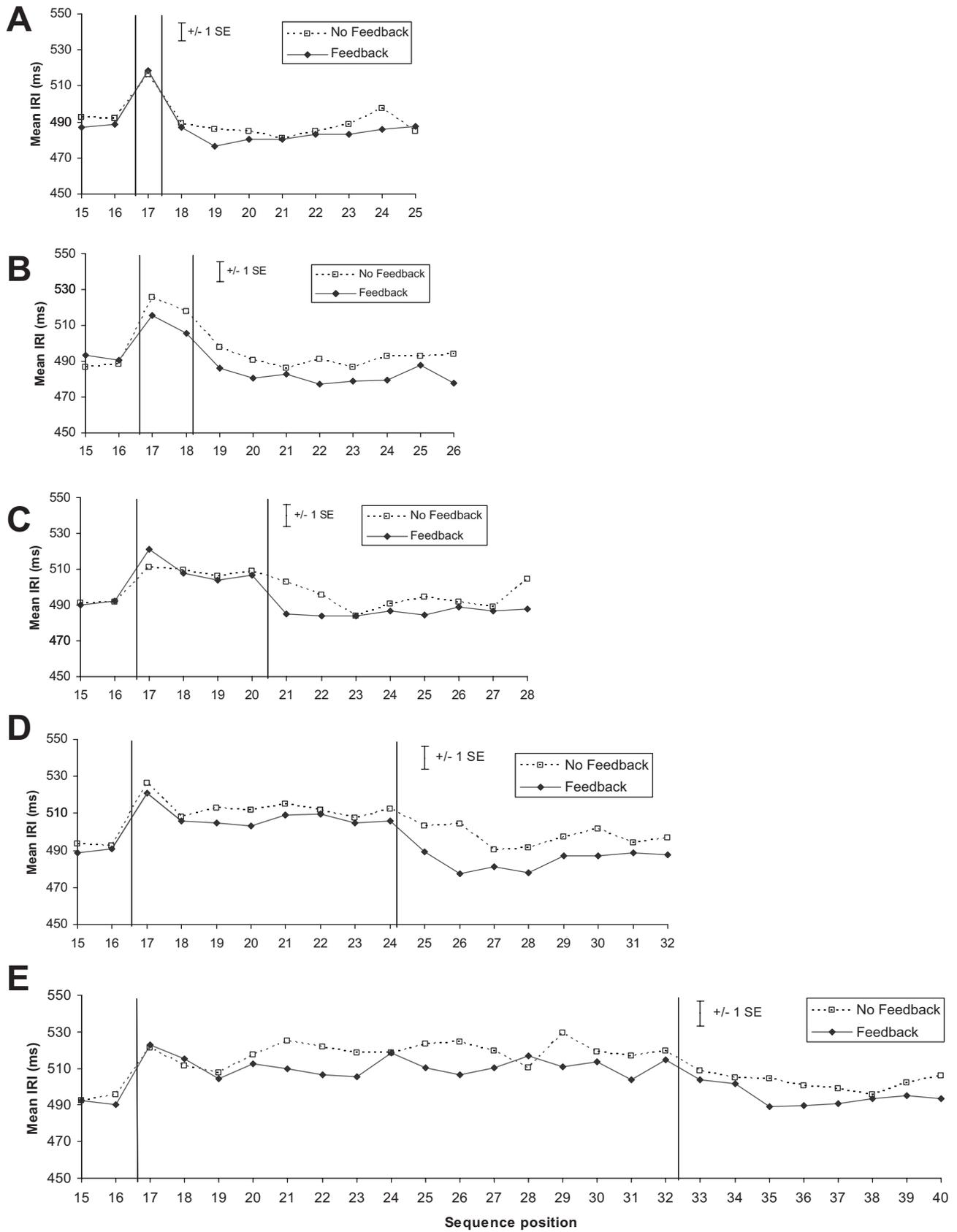


Figure 4 (opposite).

Table 1
Best-Fitting Parameters and Goodness-of-Fit Values for
Relaxation Curves (Equation 1) From Experiment 1

N	Feedback	Slope	Asymptote	VAF
1	present	2.91	-7.55	93%
	absent	3.21	-3.27	84%
	M	3.06	-5.41	89%
2	present	2.10	-9.37	89%
	absent	1.94	0.43	92%
	M	2.02	-4.47	90%
4	present	3.50	-4.01	93%
	absent	1.28	2.71	55%
	M	2.39	-0.65	74%
8	present	2.45	-5.88	77%
	absent	1.13	5.66	70%
	M	1.79	-0.11	74%
16	present	1.00	1.97	89%
	absent	1.17	10.97	84%
	M	1.08	6.47	86%
M	present	2.39	-4.97	88%
	absent	1.74	3.30	77%
	M	2.07	-0.83	83%

iment 2 was identical to Experiment 1, except that participants used an M-AUDIO Keystation 49e unweighted piano keyboard instead of the drum pad that was used for tapping responses.

All participants performed a single melody that has been used in previous research (Pfordresher, 2005, 2008). The melody comprised the pitches [C4 D4 E4 G4 F4 E4 D4 E4] and was played repeatedly without pausing between repetitions. The melody was performed with a fixed finger-key mapping so that participants would not have to shift hand position while performing. Because many participants were not musically trained we incorporated an alternate form of music notation (described in Pfordresher, 2005), in which successive notes are represented as a row of numbers beneath images of the right hand with the relevant finger highlighted. The notation for the melody performed here was thus represented as the numerical row [1 2 3 5 4 3 2 3], where 1 indicates the thumb and 5 indicates the pinky. On the keyboard, numbers 1-5 were arranged in a row above the corresponding piano keys, with arrows pointing to the requisite piano key. As in previous studies, nonpianists quickly learned this configuration. Feedback pitch contents matched the most recent produced events.

Procedure

The only procedural change in Experiment 2 was that at the beginning of the session, participants were required to learn and memorize the stimulus melody. The experimenter described the notation system and had participants play through the melody once to ensure that the participant understood the notation system. Then the participant performed the melody in view of

the notation until he or she believed the melody had been memorized. Then the experimenter removed the notation and had the participant perform the melody from memory; three consecutive error-free repetitions was the criterion for successful memorization. If the participant had difficulty recalling the melody after notation was removed, they were told to practice the melody in view of notation again. Following successful memorization, participants practiced playing the melody from memory in synchrony with a metronome and went on through the remaining procedure, as in Experiment 1.

Data Analysis

We focused on measures of timing (i.e., IRI-diff) in Experiment 2, as in Experiment 1. One critical difference between the two tasks is that participants can make pitch errors when producing a melody (i.e., hitting the wrong key). Pitch errors are important both because they function as a measure of disruption and because perturbations in performed timing are often associated with production errors (Maidhof, Rieger, Prinz, & Koelsh, 2009; Ruiz, Jabusch, & Altenmüller, 2009). However, asynchronous feedback does not typically increase error rates significantly (Pfordresher, 2003) and the current experiment bore out this trend. In the current data set, the mean error rate per trial was 0.2%. Only 2% of trials in the current experiment featured any kind of an error, and of these trials 91% (81 trials) had only one error. Most important, experimental manipulations yielded no effects on error rates and preliminary analyses suggested that the inclusion or exclusion of IRIs associated with errors had negligible effects on results. Thus, in order to maintain parity with Experiment 1, we retained IRIs associated with errors in the analyses reported here.

Results

We analyzed IRI-diff scores as in Experiment 1. Results from control trials differed somewhat from Experiment 1. Whereas IRI-diff scores for segments 2 and 3 in control trials were close to zero in Experiment 1, scores from Experiment 2 suggested a slight tendency to speed up in segment 2 [M IRI-diff = -19.9, $t(22) = -3.19$, $p < .01$, two-tailed] though not in segment 3 ($M = -5.11$, n.s.).

As in Experiment 1, we conducted analyses like those reported below with the additional factor musical training. No effects related to musical training emerged and so we only report analyses that are averaged across all participants.

Within-Segment Means

Figure 5 shows IRI-diff scores from Experiment 2. Means across segments 2 and 3 are shown in Figure 5A. IRIs slowed in segment 2 while delays were present; the degree of slowing

Figure 4 (opposite). Time series data from Experiment 1 showing mean IRI across different segment 2 lengths (panels A-E) and feedback presence in segment 3. Each data point represents the mean IRI across participants beginning at that serial position, ending at the next serial position. Error bars in each panel represent mean SE (+/-) across all data points. Each panel begins with the final two events of segment 1 (events 15 and 16); vertical bars in each panel highlight the IOI(s) in segment 2 and events to the right of this region comprise events from segment 3.

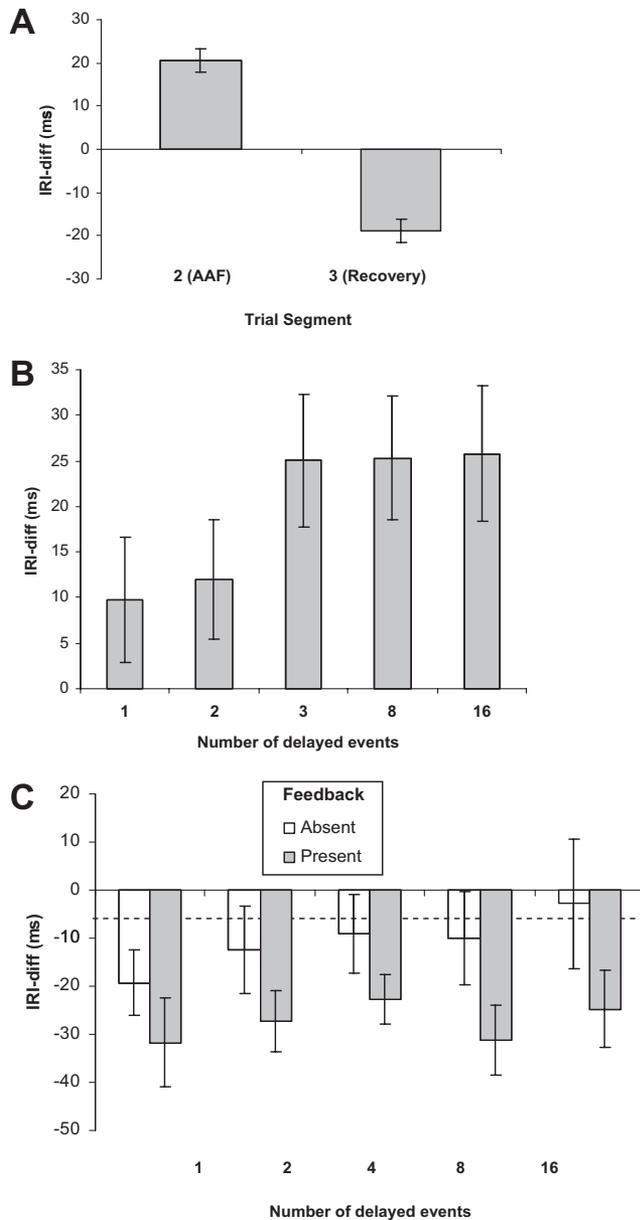


Figure 5. Segment means from Experiment 2; error bars represent one standard error of the mean (between participants). A: Mean IRI-diff scores for different trial segments in Experiment 2 across all conditions. B: Mean IRI-diff scores for segment 2 (AAF) by segment 2 length (# of events). C: Mean IRI-diff scores for segment 3 (recovery) by segment 2 length and feedback presence within segment 3; the dashed line represents the mean IRI-diff scores for segment 3 in control trials.

was comparable to that found in Experiment 1 (M IRI-diff in segment 2 for Experiment 1 = 17.0, $SE = 2.2$ for Experiment 2 = 19.6, $SE = 3.2$). However, IRI-diff scores in segment 3 suggested general overcompensation in Experiment 2 whereas comparable data from Experiment 1 suggested a return to the timing seen in segment 1. We conducted paired t -tests (two-tailed) across participants between each segment shown in Figure 5A and the corresponding mean for normal feedback

control trials. In both cases the contrast was significant [for segment 2, $t(22) = 5.88$, $p < .01$, for segment 3, $t(22) = 2.08$, $p < .05$].

The effect of the number of delayed events (segment 2 length) on IRI-diff scores in segment 2 is shown in Figure 5B. In all cases IRIs slowed in segment 2 and the main effect of segment 2 length was not reliable. Segment 2 lengths of two events and greater yielded IRI-diff scores that were significantly greater than 0 [for length 2, $t(22) = 1.81$, $p < .05$, for lengths of 4, 8 and 16 $t(22) > 2.51$, $p < .01$, one-tailed], and all conditions yielded mean IRI-diff scores that exceeded the mean for control trials, $t(22) > 4.30$, $p < .01$ for each.

Results from segment 3, shown in Figure 5C, address the degree to which participants recovered from the effect of asynchronous feedback after asynchronies were removed. The ANOVA yielded only a significant main effect of feedback presence, $F(1, 22) = 5.21$, $MSE = 3140.01$, $p < .05$, $\eta_p^2 = 0.24$, with IRI-diff scores being more negative when feedback was present in segment 3 ($M = -9.3$) than when feedback was absent ($M = -2.9$). No effects of segment 1 length were found ($p = .40$, $\eta_p^2 = 0.05$). In particular, unlike Experiment 1, in Experiment 2 there was no evidence of diminished recovery in segment 3 when segment 2 included 16 delays.

Time Series Analyses

As in Experiment 1, we further investigated the pattern of IRI timing in different segments by analyzing time series across segments 2 and 3, shown in Figure 6. Similar to Experiment 1, the effect of asynchronous AAF was immediate and generally consistent across events in segment 2. Likewise, recovery from AAF in segment 3 occurred rapidly, leading to overcompensation with IRIs in segment 3 faster than the prescribed rate. In certain conditions of Experiment 2 there appeared to be a tendency for recovery from AAF to be faster when feedback was present in segment 3 than when feedback was absent; though this tendency was not as consistent as in Experiment 1. As we did in Experiment 1, we fit the relaxation model (Equation 1) to the data of segment 3 starting with the last event of segment 2. Best fitting parameter values and VAF values are shown in Table 2. Best fitting asymptote parameters were highly consistent (and negative) across conditions, verifying the data shown in Figure 5A, but did not reflect the effect of feedback presence (Figure 5C). Rather, the effect of feedback presence appeared in different relaxation time (slope) values, that although variable, were in general higher when feedback was present than when feedback was absent from segment 3.

Discussion

In many critical respects, the data from Experiment 2 replicated the data from Experiment 1. The effect of AAF on IRI timing was rapid, uniform across delays, but dissipated rapidly after AAF removal as would be expected from the phase perturbation account described earlier. In addition, the presence of auditory feedback enhanced participants' tendency to speed up after the removal of AAF, though asymptotic performance was similar regardless of feedback presence.

At the same time, certain details of Experiment 2's results differed from Experiment 1. The most striking departure was the overarching tendency for overcorrection when AAF was removed, seen only in certain conditions of Experiment 1. Thus, Experiment 2 (but not Experiment 1) yielded support for the idea that participants attempt to adapt to asynchronous AAF but are unsuccessful in doing so, leading to a compensatory effect in segment 3 but not an adaptation effect in segment 2 (cf. Houde & Jordan, 1998, 2002). As in Experiment 1, this tendency was stronger when feedback was present than when feedback was absent in segment 3. Related to this, feedback presence in Experiment 2 did not appear to influence asymptotic performance in segment 3 whereas it did for Experiment 1 (cf. Tables 1 and 2). This difference may relate to the different tasks used. It is possible that the presence of sequential pitch feedback associated with sequence production (Experiment 2) is less likely to dissociate from one's actions than monotonic pitch feedback associated with tapping (Experiment 1).

A second, more theoretically important difference from Experiment 1 was that recovery in segment 3 did not vary with the number of delays present in segment 2, providing stronger evidence than in Experiment 1 for disruption of phase as opposed to period. Recall that in Experiment 1, recovery was weaker after participants experienced 16 delayed feedback onsets. Thus the tendency to "lose track" of timing—evident for trials of length 16 in Experiment 1—was not apparent in Experiment 2. We suggest that this difference relates to the representation of time in each context. When producing a sequence, as in Experiment 2, performers may conceptualize time in a hierarchical fashion, particularly when producing an 8-event sequence as participants did here (Vorberg & Hambuch, 1978; Vorberg & Wing, 1996; Shaffer, Clarke, & Todd, 1985). By contrast, the organization of time for isochronous tapping (Experiment 1) may be serial (e.g., Wing & Kristofferson, 1973). One result of these differences in timing could be that the subjective length of segment 2 was shorter for participants in Experiment 2 than in Experiment 1. For instance, when segment 2 included eight delays, the length of this segment could be conceptualized as "one repetition" (of the sequence) in Experiment 2 rather than as eight independent events. As a result of this, hierarchical representations used in Experiment 2 may have shortened the subjective length of segment 2, perhaps due to the enhancement of future-orientated attending that is associated with higher-order sequential organization (Jones & Boltz, 1989), given that incoherent organizations have been found to lead to temporal overestimation (Boltz, 1995).

Experiment 3

Experiment 3 was designed to further test the separation between sequencing and timing in the use of auditory feedback (cf. Pfordresher, 2003, 2006) by examining the temporal dynamics of disruption from *serially shifted* auditory feedback, which was presented instead of asynchronous feedback during segment 2 of trials. More specifically, we used a lag-1 serial shift, for which each keypress results in the pitch associated with the previous keypress. Serial shifts of various lags and leads (leading shifts present feedback events intended for the future) have been tested and all have produced a consistent result: they increase error rates while generally sparing timing, in particular, mean IRIs (Pfordresher, 2003, 2005, 2008; Pfordresher & Palmer, 2006). In con-

trast, other alterations of feedback pitch, such as presenting random or quasi-random feedback events, do not disrupt production (Finney, 1997; Pfordresher, 2005).

Another change we introduced in Experiment 3 involved trial lengths. Specifically, we lengthened the range of events that could be present in segment 2, and lengthened segment 3 in all trials. Preliminary analyses of previous data sets (which did not include the same design or stimuli as used in Experiment 3) suggested serial shifts may not start yielding an effect until several events have passed. Thus segment 2 lengths in Experiment 3 were 1, 8, 16, or 32 events rather than 1, 2, 4, 8 or 16 events. Likewise, segment 3 was lengthened to 16 events.

Method

Participants

Twenty-seven students from UB (mean age = 18.9, range 18–26) volunteered to participate in exchange for course credit in introductory psychology. Eight of these were female and 19 were male. Twenty-four were right-handed and three were left-handed. No participants reported hearing impairment or motor impairment of the right hand. Twenty participants (83%) reported at least one year of musical training. Mean years of training among these participants was 4 years (range 1–11, mode across participants = 0). Five participants reported more than a year of training on the piano ($M = 5.4$, range 2–11); however only one participant reported practicing currently (furthermore, that person reported only 1 hour per week). Three participants reported having absolute pitch. Thus the sample of Experiment 3 was on the whole more musically trained than in other experiments, but past research demonstrated that the disruptive effect of serial shifts is similar for both musicians and nonmusicians (Pfordresher, 2005, 2008). Likewise, analyses of the current data that included musical training as a factor (which also incorporates participants with absolute pitch), like those reported for Experiments 1 and 2, did not show interactions between musical training and experimental factors; the same qualitative effects were observed for both groups.

Materials, Conditions, Apparatus, and Procedure

The apparatus used in Experiment 3 was identical to that used in Experiment 2. Likewise, the same 3-segment trial structure was used as in Experiments 1 and 2, with AAF being presented in segment 2, giving way to either no feedback or normal feedback in segment 3. However, we altered the type of feedback manipulation as well as the different lengths of segments 2 and 3 that a participant could experience.

AAF in Experiment 3 comprised lag-1 serial shifts of feedback pitch, a manipulation that has been described in previous papers (Pfordresher, 2003, 2005, 2008; Pfordresher & Palmer, 2006) and is implemented by the program FTAP (Finney, 2001). Specifically, FTAP maintains the content of each produced pitch in a buffer. At the time of each keypress, it then releases the pitch content associated with the previous keypress. At the time of the transition from segment 1 (normal feedback) to segment 2 (serial shifts), the participant hears the same pitch twice, first as normal feedback and then as a serial shift.

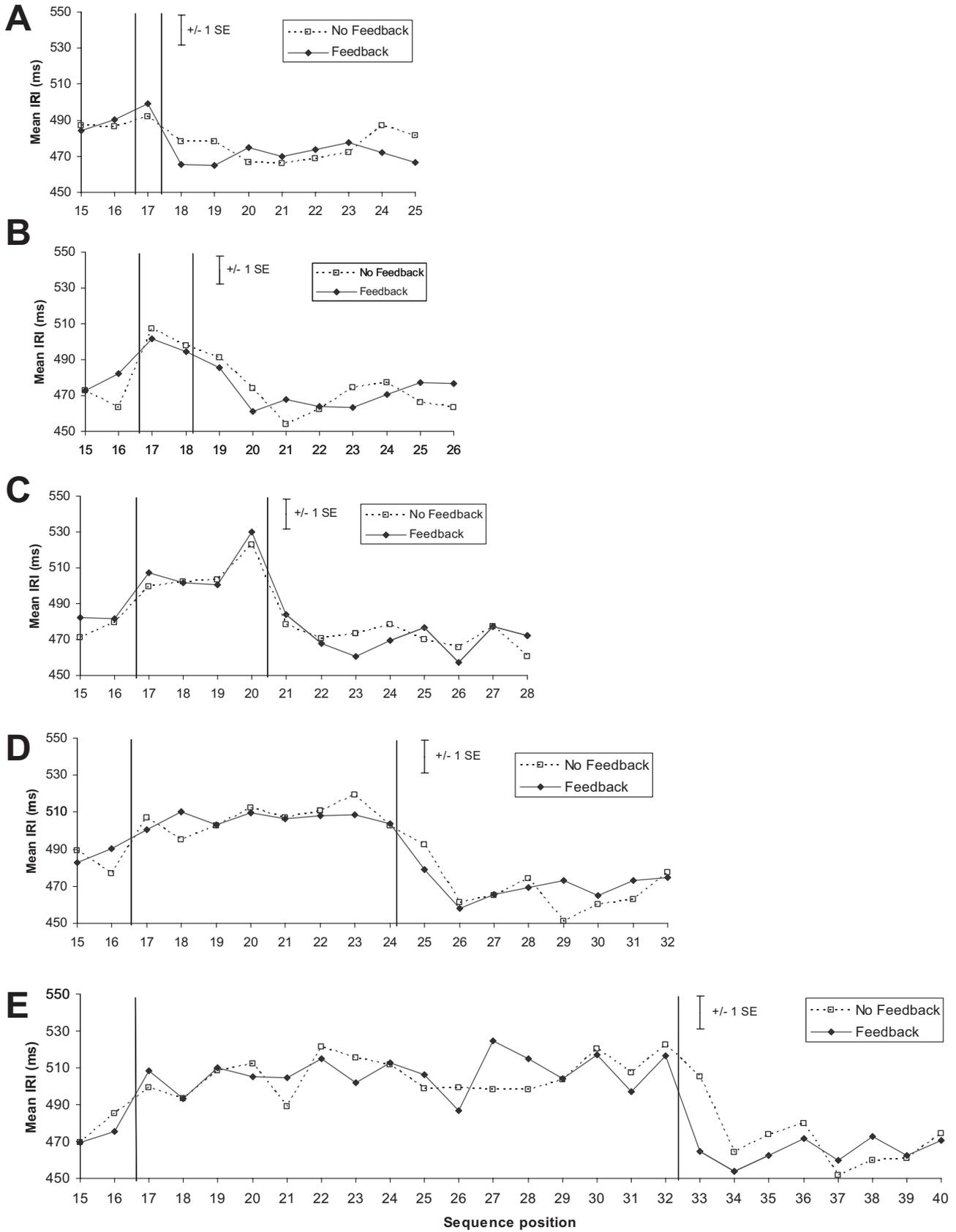


Figure 6 (opposite).

Table 2
Best-Fitting Parameters and Goodness-of-Fit Values For
Relaxation Curves (Equation 1) From Experiment 2

N	Feedback	Slope	Asymptote	VAF
1	present	25.46	-11.35	85%
	absent	1.94	-7.89	48%
	M	13.70	-9.62	66%
2	present	1.48	-21.04	69%
	absent	1.07	-23.51	72%
	M	1.27	-22.28	70%
4	present	2.06	-21.44	91%
	absent	2.54	-19.31	92%
	M	2.30	-20.38	92%
8	present	2.17	-21.30	84%
	absent	1.13	-25.97	74%
	M	1.65	-23.63	79%
16	present	18.94	-25.25	90%
	absent	1.01	-25.99	83%
	M	9.97	-25.62	87%
M	present	10.02	-20.08	84%
	absent	1.54	-20.53	74%
	M	5.78	-20.30	79%

With respect to the length of segment 2, we added a condition that featured a run of 32 serially shifted events, which is longer than the longest run used in Experiments 1 and 2. In addition we excluded segment 2 lengths of two and four events to accommodate the extra time added by the longer 32-event trials. Thus, trials with serial shifts could include segment 2 lengths of 1, 8, 16 or 32 events. Also, as in Experiments 1 and 2, baseline trials in which no alteration was presented in segment 2 featured the equivalent of 16 segment 2 events.

Segment 3 was also extended to 16 events. This was done in order to give participants more recovery time, given our prediction that participants would not recover in Experiment 3 as in Experiments 1 and 2.

In Experiment 2, where we did not expect effects on error rates (and none were found), all participants played the same 8-note melody. However, because we did expect serial shifts to increase error rates, we had different participants learn and perform different melodies so that we could be certain that effects of error rates were not limited to a specific sequence. Each participant played one of four melodies that were chosen from the same set described in other papers (Pfordresher, 2005, 2008). These melodies were designed to differ with respect to starting pitch (C or G) and contour (smooth versus alternating). All melodies comprised eight events and used the same set of five pitch classes that were used in Experiment 2. Of the 27 participants in Experiment 3, seven (26%) performed the same melodies as those who were in Experiment 2.

The procedure of Experiment 3 was identical to Experiment 2.

Data Analysis

The primary dependent measure of disruption in Experiment 3 was pitch errors rather than timing. Pitch errors were analyzed by an algorithm that compares the vector of produced pitch events to a vector of an ideal sequence and identifies the fewest number of changes to the produced vector necessary to equate the two (Large, 1993; Palmer & van de Sande, 1993, 1995). The number of errors found within each segment was divided by the number of events in each segment. As in Experiments 1 and 2, we computed difference scores to gauge disruption by and recovery from AAF, only here difference scores were based on differences in error rates (err-diff), not IRIs, of segments 2 and 3 with segment 1.

Results

Error rates overall in Experiment 3 were low ($M = 1.4\%$) but were significantly greater than zero according to a single-sample t -test, $t(26) = 5.39$, $p < .01$, and were also greater than error rates in Experiment 2 ($M = 0.2\%$), according to a two-sample t -test, $t(48) = 4.43$, $p < .01$. Low error rates are common in piano performance (though often higher than the current data set when more complex materials are used); moreover, we will show that error rates fluctuated considerably according to experimental variables. During control trials, there was a tendency for error rates to diminish through the trial [M err-diff for segment 2 = -1.5% , $t(26) = -3.48$, $p < .05$, for segment 3 = -0.8% , n.s.].

We analyzed produced timing as well. No experimental factors reliably influenced timing, and we do not consider the role of timing in Experiment 3 further.

Within-Segment Means

Figure 7 shows err-diff scores from Experiment 3. Means within segments 2 and 3 are shown in Figure 7A. Err-diff scores differed across segments, $t(26) = 3.66$, $p < .01$. On average, error rates in segment 2 did not differ from segment 1 (though we will show this to be highly qualified by segment 2 length). Furthermore, in stark contrast to Experiments 1 and 2, err-diff scores were substantially higher in segment 3 than in segment 1. Given that participants did improve somewhat during control trials, we conducted t -tests contrasting the means in Figure 7A with the corresponding means from control trials (trials for which a 16-event segment 2 featured normal feedback); each contrast was significant [for segment 2, $t(26) = 6.0$, for segment 3, $t(26) = 6.3$, $p < .01$ for each].

The effect of segment 2 length on err-diff scores in segment 2 is shown in Figure 7B. The effect of segment 2 length was significant, $F(3, 78) = 6.62$, $MSE < .001$, $p < .01$, $\eta_p^2 = 0.25$, reflecting an important difference in the effect of serial shifts versus the effect of asynchronous feedback. In particular, the only condition leading to a significant increase in error rates, compared to segment 1, was for segment 2 lengths of 32 events, $t(26) = 2.40$, $p <$

Figure 6 (opposite). Time series data from Experiment 2 showing mean IRI across different segment 2 lengths (panels A–E) and feedback presence in segment 3. Each data point represents the mean IRI across participants beginning at that serial position, ending at the next serial position. Error bars in each panel represent mean $SE (+/-)$ across all data points. Each panel begins with the final two events of segment 1 (events 15 and 16); vertical bars in each panel highlight the IOI(s) in segment 2 and events to the right of this region comprise events from segment 3.

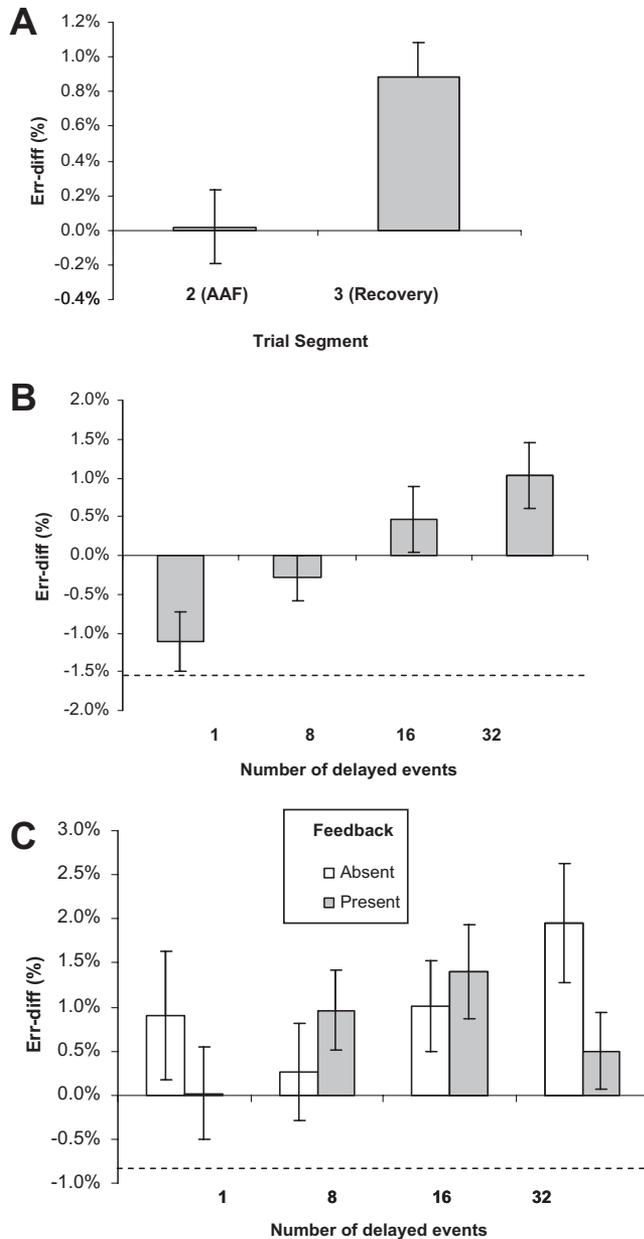


Figure 7. Segment means from Experiment 3; error bars represent one standard error of the mean (between participants). A: Mean err-diff scores for different trial segments in Experiment 3 across all conditions. B: Mean err-diff scores for segment 2 (AAF) by segment 2 length (# of events); the dashed line represents the mean err-diff scores for segment 2 in control trials. C: Mean err-diff scores for segment 3 (recovery) by segment 2 length and feedback presence within segment 3; the dashed line represents the mean err-diff scores for segment 3 in control trials.

.05 (one-tailed)⁴. However, err-diff scores for segment 2 lengths of 8 and 16 were significantly higher than err-diff scores during control trials (in which participants improved slightly); for length 8, $t(26) = 4.17$, for length 16, $t(26) = 4.67$, $p < .01$ for each. Thus in both cases performance was worse than with normal feedback, even though trials with segment 2 lengths of eight events generated

slightly negative err-diff scores. The negative err-diff scores for segment 2 length of one were comparable to the improvement seen in control trials ($M = -1.5\%$, see dashed line in Figure 7B). The main effect of segment 2 length was still present in an ANOVA that removed this condition, $F(2, 52) = 5.29$, $MSE < .001$, $p < .01$, $\eta_p^2 = 0.20$, further verifying the fact that disruption accumulates for successive presentations of serially shifted AAF.

Results from segment 3 are shown in Figure 7C. As mentioned before, there was an overall tendency for error rates to be greater than zero (and greater than control trials). Although Figure 7C shows apparent fluctuations in err-diff scores the ANOVA yielded no significant main effects or interaction.

Time Series Analyses

We plot the pattern of mean error rate (averaged across participants and trials) for each of the eight experimental conditions in Figure 8. Following the trend of our analyses of segment means, these data show a very different pattern of disruption over time than did the data from Experiments 1 and 2. Most apparent is the fact that error rates, unlike mean IRIs, fluctuate dramatically across positions in segments 2 and 3. We focus first on these fluctuations as they occur in segment 2.

Although mean error rates were low overall, as mentioned before, error rates associated with certain positions could be as high as 10% when participants experienced serially shifted feedback, which is a high error rate for piano performance (error rates on the order of 4% are more common for performances from memory, e.g., Palmer & Pfordresher, 2003). More to the point, peaks that emerged in error rates during segment 2 appeared to be associated with the beginnings of the 8-note sequence, such as the peaks at positions 25 and 33 when participants experienced 32 serial shifts (Figure 8D). This pattern of results suggests that the cumulative effect of serial shifts that was apparent in analyses of segment means may be a result of how many sequence beginnings occurred within sequences. In order to test this possibility, we ran a regression analysis on the mean error data of segment 2 for conditions with 16 and 32 serial shifts, using both position within segment 2 (1–16 or 1–32) and position within sequence (1–8) as predictors. Regressions for the length 32 condition and for the aggregated data of both length conditions were significant ($R^2 = .27$ for length 32, $R^2 = .25$ for aggregated data, $p < .01$ for each) and lead to the same conclusion. In each case both predictors contributed independently to error rates ($p < .05$ in every case). Each variable predicted an opposing trend in the data; the relationship between segment position and mean error rates was positive [$r(30) = .33$ for length 32, $r(46) = .35$ for aggregated data], but the relationship between sequence position and mean error rate was negative [$r(30) = -.31$ for length 32, $r(46) = -.25$ for aggregated data]. There are thus two tendencies in segment 2, a

⁴ As stated earlier, all single-sample t -tests for segment 2 were one-tailed, given that the a priori hypothesis is that AAF will lead to increases in the measure of disruption being assessed (IRIs or error rates). In Experiment 3 there is clearly a tendency for error rates in segment 2 to be lower than in segment 1 when segment 2 includes only a single event (the mean err-diff score is negative). However, this difference is contrary to our one-tailed hypothesis and is thus considered nonsignificant.

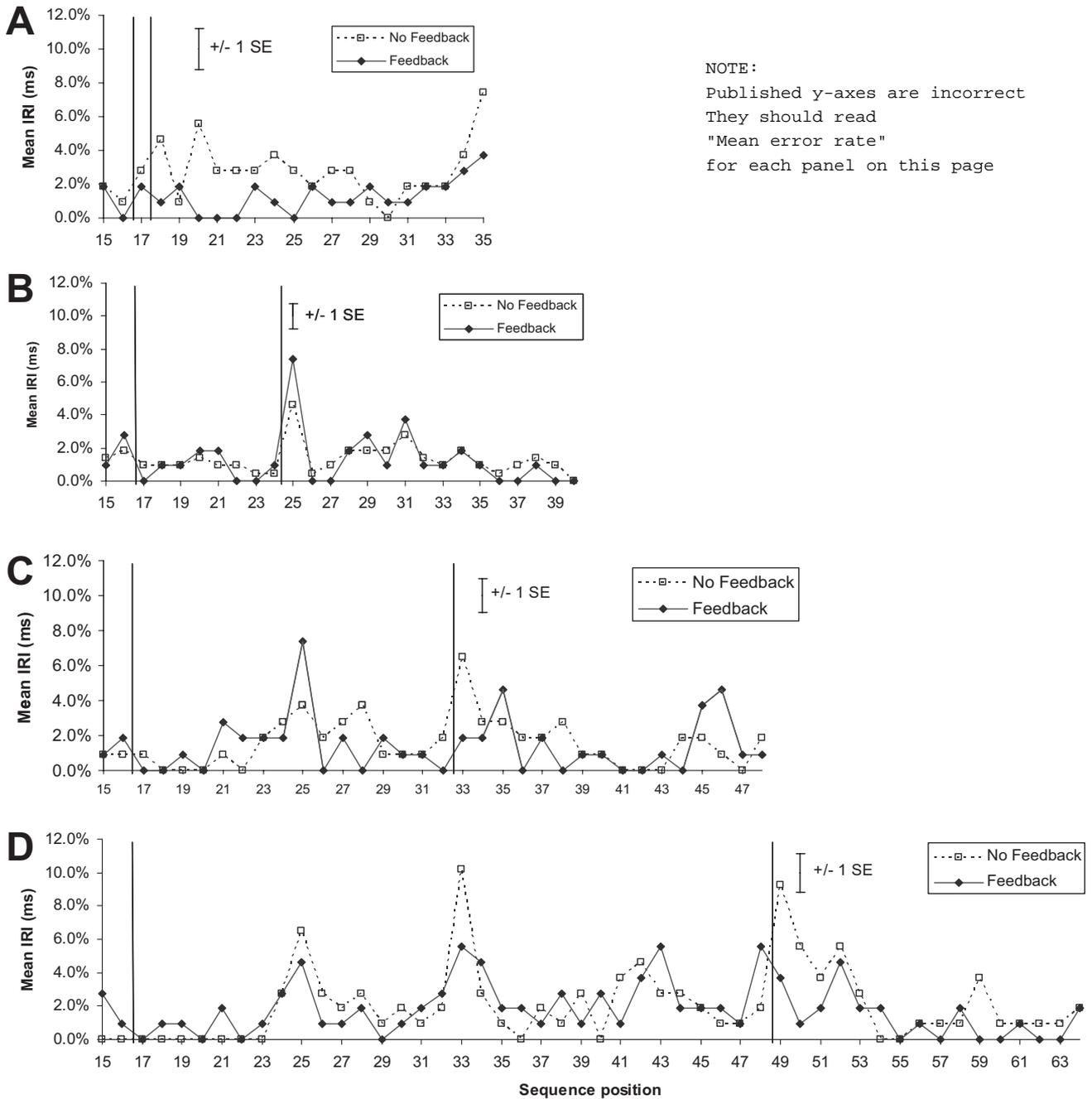


Figure 8. Time series data from Experiment 3 showing mean error rates across different segment 2 lengths (panels A–D) and feedback presence in segment 3. Each data point represents the mean error rate across participants beginning at that serial position, ending at the next serial position. Error bars in each panel represent mean SE (+/–) across all data points. Each panel begins with the final two events of segment 1 (events 15 and 16); vertical bars in each panel highlight error rates in segment 2 and events to the right of this region comprise events from segment 3.

tendency for increased error rates at the beginnings of repeated sequences, and a tendency for a gradual increase in error rates throughout the segment. Both factors contribute to the segment mean results, in that with longer segment 2 lengths there are both more sequence beginnings and more segment events.

The second tendency apparent in the time series data was for a localized error peak to occur near the beginning of segment 3. This tendency contrasts sharply from the timing data of Experiments 1 and 2, where rapid recovery (or overcompensation) appeared immediately. A multiple regression on the aggregated data of all four

segment 2 length conditions (all of which shared the same segment 3 length) was marginally significant ($p = .07$), with the predictor sequence position contributing significantly [$r(62) = -.27, p < .05$]. The fact that segment position did not contribute significantly suggests that reduction in error rates during segment 3, though apparent in Figure 8, was not robust. This bears out the implication from the segment mean analyses that participants did not truly recover from the effects of serially shifted feedback. In addition, we ran follow-up ANOVAs on err-diff scores for segment 3 (averaged across position) after removing the first 1–3 events in the segment. In each case mean err-diff scores were significantly greater than zero, which verifies the interpretation that serial shifts led to disruptive effects that persisted in segment 3 beyond any disruptive effect specific to the transition from segment 2 to segment 3.

These tendencies were not observed during control trials (results from a similar regression analysis were not reliable), with the exception that the switch to absent feedback during segment 3 (which occurred in half of the control trials) caused a brief elevation of error rates like that seen in AAF conditions at the beginning of segment 3. Note, however, that the elevation in AAF conditions (unlike control trials) occurred whether or not feedback was present in segment 3.

Discussion

In Experiment 3 we documented that the temporal dynamics of disruption from serial shifts differ from the temporal dynamics of disruption from asynchronous feedback. The disruptive effects of serial shifts built up gradually, varied with sequence position, and did not vanish when shifts were removed. Furthermore, there was no evidence that the presence or absence of auditory feedback during segment 3 (the recovery segment) influenced behavior after the removal of serial shifts.

The influence of serial shifts on error rates while shifts were present matches the theoretical perspective mentioned earlier. We proposed that serial shifts degrade sequence memory. This degradation in principle would occur as a byproduct of the fact that auditory feedback introduces activations to nodes in a shared representation of sequence structure, common to perception and action (Pfordresher, 2005, 2006; cf. Hommel et al., 2001; MacKay, 1987). When serial shifts are introduced, activations are directed toward events that are not planned for the current position, but are nevertheless somewhat activated by virtue of the dynamics of activation and decay (see Figure 1). As a result, feedback would disrupt the pattern of activations across time that is necessary for appropriate sequencing, thereby weakening associations between sequence event nodes (in the shared representation) and serial positions (used for generating actions).

Along with the cumulative effect of serial shifts, we also observed a tendency for errors to increase at beginnings of sequences while participants were experiencing serial shifts (for a similar result in performances with normal feedback see Palmer & Drake, 1997). This effect suggests that the accuracy of retrieval is particularly vulnerable when the performer initiates a motor plan, as our performers presumably did each time they repeated the 8-note sequence. This implication is consistent with other research suggesting that performers represent sequential boundaries as “performance cues” to facilitate memorization (Chaffin & Imreh, 2002;

Chaffin, Logan, & Bergosh, 2009). Recent research suggests retrieval is enhanced at such boundaries during recall without time constraints (during transcription, Chaffin, Ginsborg, & Dixon, 2009). The present findings modify this conclusion, in suggesting that such points—though salient—may also be unstable.

With respect to segment 3, the recovery segment, the data do not clearly support the idea that recovery happened. Segment means for error rates were comparably high, in some cases higher, in segment 3 as compared to segment 2. Time series analyses suggest some improvement in error rates, though this improvement was not as robust or as rapid as was seen in Experiments 1 and 2. It is possible, of course, that a longer segment 3 could have led performers to full recovery. Taking that possibility into account, a conservative conclusion would be that recovery is slower from serial shifts than from asynchronies. This conclusion is also in line with the theoretical framework proposed here, in that degradation of associations between events and serial positions brought on by AAF should not necessarily revert to their original state once AAF is removed but may gradually regain their initial associations.

General Discussion

The results of the three experiments reported here both confirm earlier findings and reveal new findings concerning the disruptive effects of asynchronous auditory feedback compared to alterations of (serially shifted) feedback contents on production. Asynchronies disrupt timing by slowing down production. The effect of asynchronous feedback is rapid, consistent across repeated asynchronies, and dissipates quickly when asynchronies are removed. By contrast, serial shifts of feedback contents disrupt accuracy by increasing pitch errors. The effect of serial shifts builds gradually, is dependent on the current sequence position, and persists after the serial shift is removed. Taken together, these results provide support for the theoretical framework underlying this research: perception and action are coordinated at separate time scales, including timing (synchrony) and sequencing (serial recall). Current results validate the attribution of different effects of feedback manipulations to different time scales of sequence representation.

A second issue that this research was designed to address concerns the role of corrective (normal) feedback after AAF is removed. The presence of normal feedback had different effects depending on whether it was preceded by asynchronous or serially shifted feedback. After participants experienced asynchronous feedback, a return to normal feedback led to overcorrection, whereas absent feedback led to a return to timing closer to the timing exhibited in segment 1. Normal feedback was not “corrective,” strictly speaking. Instead, feedback presence may influence the time it takes participants to reach asymptotic performance levels (Experiments 1 and 2) as well as the asymptotic rate they attain (Experiment 1). By contrast, feedback presence had no reliable effect on behavior following serially shifted auditory feedback. As mentioned before, the effects of feedback presence after asynchronous AAF can be interpreted as resulting from dissociations between perception and action caused by the asynchronies (cf. Sato & Yasuda, 2005). By this logic, it is possible that serially shifted feedback does not similarly dissociate from actions, a claim consistent with a previously articulated view that alterations of contents are more disruptive when the feedback sequence bears

some similarity to the action plan than if the feedback sequence is independent of the action plan (Pfordresher, 2005, 2006, 2008).

Certain aspects of these data are consistent with previous literature on performance. For instance, the rapid effect of perturbations in auditory feedback, followed by rapid recovery, was documented some time ago by Wing (1977). Similar effects likewise have emerged in more recent research on synchronization, in which variations of metronome timing have effects on synchronization that are comparable to the effects of feedback asynchronies on continuation (e.g., Large et al., 2002; Repp, 2000, 2001a, 2002, 2003). In keeping with these results, Repp (2001a, 2001b) proposed, as we do, that changes in timing based on perturbations of event onsets are due to fluctuations in the phase of the internal timekeeper more so than its period. Alterations of feedback contents are less well explored and as such less precedent exists for their effects. Most alterations of feedback contents have involved frequency-based shifts of feedback during vocal production, allowing for compensatory alterations of produced sounds, and their effects are often rapid (within about 100 ms, e.g., Liu & Larson, 2007). However, the idea that the motor system gradually adapts to alterations in feedback contents is consistent with the procedure of Houde and Jordan (1998, 2002), who altered formant structure in speech feedback, leading to the perception of altered vowels resulting from articulation. Analogous to our effects of serial shifts, they incorporated a one-hour exposure period in order to evoke effects of their formant shifts, a lengthy time span that was apparently necessary to yield an effect (Howell, 2004, p. 69).

An unavoidable limitation of the current research is that the temporal dynamics of disruption (slow versus rapid) co-vary with the type of disruption observed (accuracy versus timing). This leads one to wonder if there is something intrinsically “fast” about fluctuations in timing or intrinsically “slow” about fluctuations in accuracy during sequence production. It is unfortunately impossible to disentangle these two aspects of the data, given that the dissociation between timing and accuracy was highly robust and reliable. However, we think it is unlikely that the temporal dynamics of each feedback manipulation are merely byproducts of the kind of dependent variable in which disruption materializes. Consider timing. Although changes in timing can certainly be invoked rapidly, certain changes in timing occur across broad timescales, leading to “tempo drift” and fractal patterns of variability in timing (e.g., Madison, 2001). Conversely, rapid changes in the accuracy of music recall across serial positions have recently been documented (e.g., Chaffin, Logan, et al., 2009). Thus we propose that the different temporal dynamics of disruption observed do in fact provide a new form of evidence, in principle independent from measures of disruption, for the dissociation between sequencing and timing.

An important question for future research involves the extent to which the kind of results reported here extend to vocal motor behavior, including speech. As we had mentioned in the introduction, the effect of serially shifted feedback on production runs counter to the claim of Howell and colleagues (e.g., Howell et al., 1983) that the effects of auditory feedback are limited to temporal synchrony. Moreover, there is reason to believe that sensorimotor associations for vocalization may differ from associations that function in manual tasks like keyboard production (also as argued by Howell et al., 1983). Their results are based on the combined effects of DAF and changes to feedback contents, whereas serial

shifts as generated here have never been used in the domain of speech (the closest approximation was reported by Müller, Aschersleben, Esser, & Müsseler, 2000). It is, of course, difficult to manipulate serial shifts in exactly the same way as we did here, which was based on MIDI technology (Finney, 2001). However, recently in our lab we have tested the effects of DAF that is designed to function like serial shifts, by using delay lengths equal to the lengths of IOIs in isochronous singing tasks. These data suggest that, at least in singing, the dissociation observed here for keyboard production generalizes across effectors (Pfordresher & Varco, 2010). Future research will test whether the dissociation also generalizes to speech.

In conclusion, the current data support a model of perception and action that is unified with respect to modality but stratified with respect to time scale. On the one hand, the generally disruptive effect of AAF demonstrates the importance of congruity between perception and action, and in general supports the idea that action planning and perception share resources (cf. Hommel et al., 2001; MacKay, 1987). On the other hand, strikingly different effects of the two alterations used here (asynchronies versus serial shifts of pitch) argue for temporal stratification within this shared representation. Loss of temporal congruity between perception and action disrupts the timing of actions, whereas loss of sequential congruity disrupts the sequencing of actions. The current data set further demonstrates that the time course over which these forms of disruption evolve differs depending on the type of alteration that one manipulates.

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