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Delayed Auditory Feedback and Movement

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It is well known that timing of rhythm production is disrupted by delayed auditory feedback (DAF), and that disruption varies with delay length. We tested the hypothesis that disruption depends on the state of the movement trajectory at the onset of DAF. Participants tapped isochronous rhythms at a rate specified by a metronome while hearing DAF (for piano tones) of differing lengths. Motion capture was used to analyze movement trajectories. Mean Inter-Response Intervals (IRIs) varied as an approximately sinusoidal function of feedback condition, with DAF causing slowed production for shorter delays and speeded production for faster delays. Motion capture analyses revealed that finger velocity at the time of DAF predicted the effect of DAF on mean IRI whereas finger position predicted the variability of IRIs. A second experiment in which participants were instructed to vary the timing of peak finger height confirmed that the effect of DAF on timing variability is directly influenced by the finger trajectory.

Keywords: delayed auditory feedback, timing, tapping, motion capture

Fluency in music performance relies in part on the timing of auditory feedback as evidenced by the disruptive effects of Delayed Auditory Feedback (DAF). The first support for this idea was discovered in speech production by Lee (1950) and Black (1951) independently; generalization to music was first reported formally by Havlicek (1968). "Disruption" can take several forms. Although the initial reports focused on errors, more recent evidence suggests that when conditions are controlled so that DAF strictly involves asynchronies between perception and action (i.e., the perceived event is associated with the most recent action), the most robust effects are on timing, including the slowing of production rate (Pfordresher, 2003; Pfordresher & Benitez, 2007; cf. Robinson, 1972 for speech) and increases in timing variability (Pfordresher, 2003; Pfordresher & Palmer, 2002; cf. Howell & Sackin, 2002 for speech). Thus perturbations of feedback timing brought about by DAF lead to commensurate disruptions of produced timing (i.e., slowing).

Perhaps the most informative characteristic of DAF's effect is that it is not uniform across delay lengths; some delays cause no disruption and the magnitude of the effect varies across delays that do cause disruption. DAF disruption therefore does not indicate complete dependence of production on synchrony of auditory feedback. Instead it has been suggested that DAF disruption occurs because certain timing relationships between actions and sounds are inherently disruptive, even when sounds are not likely to be interpreted by the producer as actual feedback (Howell, Powell & Kahn, 1983). In this context, the DAF paradigm becomes a way to explore stable coordinative states between perception and action. But why are certain phase relationships more disruptive than others? We here test whether the answer lies in relating the timing of DAF onsets to kinematic states within the movement trajectory.

Recent research that has examined the effect of DAF on rhythmic finger tapping (as well as musical keyboard production) demonstrated that the best predictor of disruption was the relative timing of feedback onsets within an inter-response interval (IRI; Pfordresher & Benitez, 2007; for similar results see Finney & Warren, 2002; Robinson, 1972). We express relative timing here as the relative phase of the DAF onset, with the current IRI constituting the referent cycle length. More formally:

$$\Phi_i = \frac{Delay_i}{IRI_i} = \frac{FeedOn_i - response_i}{response_{i+1} - response_i}$$

In which *FeedOn* denotes the timing of a feedback onset, *response* denotes the timing of a response typically associated with the onset of a feedback event (e.g., pressing a piano key) and i indexes sequence position. Note that Φ_i can be greater than 1 if a delay is longer than the current IRI, although such conditions are not used in the current research. In the current research, which involves rhythmic tapping, responses are considered to be times at which the finger makes contact with the response surface. For resonant sounds (as in vocal production or wind instruments) responses are the times at which aspiration leads to vibrations within the resonant chamber that are associated with sound.

The fact that DAF disruption is predicted by the relative phase of a delay, however, does not on its own explain why certain relative phases are more disruptive than others. We suggest that disruptive relative phase relationships may be determined in part

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by the dynamics of movement states between responses. Specifically, instantaneous characteristics of a movement pattern may be associated with movement toward or away from a goal. DAF may disrupt produced timing because it counteracts the relationship of the current movement state with respect to this goal. For instance, DAF may prove most disruptive when it coincides with upwards movements, and may slow production, due to the fact that auditory events are usually associated with downward movements.

Previous accounts of DAF disruption make differing claims about the role of movement. One theory that is consistent with a movement-related account is the EXPLAN theory of production (Howell, 2004; cf. Howell et al., 1983). This theory claims that altered auditory information can cause disruption by perturbing the timing of execution (Howell, 2001). Thus, EXPLAN limits DAF disruption to production rate (a claim that has received some support in music production, Pfordresher, 2003; Pfordresher & Benitez, 2007) and leaves open the possibility that effector movements may be linked to the effect of DAF. EXPLAN, however, does not make explicit claims about the kind of movement states at which the system is most vulnerable to disruption by DAF.

Another influential theory suggests that DAF disruption is independent of movements. Node Structure Theory (MacKay, 1987) attributes DAF disruption to changes in the sensitivity of nodes in a neural network that are used for both perception and action. After a node is used to trigger an action it enters a period of hyposensitivity followed by a period of hypersensitivity; susceptibility to DAF disruption peaks during the latter phase. Importantly, these nodes are thought to trigger other nodes used to guide movements; thus the locus of the effect of DAF according to Node Structure Theory is distinct from the level of architecture responsible for guiding movement.

Finally, another recent theory of perception and action can be interpreted in two ways with regard to the role of movement in DAF disruption. The Theory of Event Coding (Hommel, Müsseler, Aschersleben, & Prinz, 2001), like Node Structure Theory, argues for a shared representation underlying perception and action planning. According to the Theory of Event Coding, planned goals for action are coded as expected perceptual outcomes, leading to a shared representation for perception and action that is specific to planned outcomes. According to this account, perception and action are not coordinated with respect to movements toward a goal and thus DAF disruption may be attributed entirely to the fact that the time of a planned outcome differs from the time of the actual outcome. On the other hand, in linking perception and action via goals the Theory of Event Coding is similar in spirit to our argument that DAF disruption causes interference because auditory events are associated with the endpoints of actions.

The research reported here was designed to address whether differences in DAF disruption can be attributed to the state of the effector(s) being used to execute an action at the time when auditory feedback sounds. We used motion capture to register finger movements in three dimensions during isochronous tapping with and without DAF. Our goal was to address whether different kinematic variables (finger position, velocity, acceleration) predict changes to timing during DAF.

To date, few studies have attempted to relate DAF disruption to movement. In the domain of speech, Zimmerman and colleagues (Zimmerman, Brown, Kelso, Hurtig, & Forrest, 1988) measured jaw movements during speech production with a strain gauge while people experienced normal feedback or DAF (with 100 or 200 ms delays). They found that disruptive DAF conditions were those in which feedback from the previous syllable occurred during the preparation of the subsequent syllable via a downward jaw movement. An earlier study, also using a strain gauge to measure jaw movements in speech, documented increased jaw lowering brought about by DAF (Sussman & Smith, 1971). They did not, however, find a significant effect of DAF on jaw velocities. Unlike Zimmerman and colleagues, Sussman and Smith did not use movement variables as a way of predicting the effect of DAF on overall timing or fluency. More recently, Moelants and colleagues used motion capture during DAF of music performance and focused on head movements (Moelants, Demey, & Leman, 2009; cf. Mataezzi, 2009). They found that the amplitude of head movements increased during DAF, possibly resulting from compensatory strategies used to overcome the effect of DAF.

Experiment 1

We investigated the link between movement kinematics and disruption caused by DAF in an experiment in which participants tapped isochronous rhythms with their right index finger at a rate specified by a metronome. During certain trials auditory feedback was delayed by a fixed proportion of the predicted IRI. The primary issue of interest was whether the finger's kinematics at the time of DAF predict the way in which DAF influences IRIs. In so doing, we also addressed the degree to which participants altered movement patterns in response to DAF.

Method

Participants

Twenty-four students from the University at Buffalo volunteered to take part in this experiment in exchange for course credit in Introductory Psychology. One participant did not report demographic information. The remaining participants included 16 women and 7 men, were all right handed, and were 20.57 years old on average (range 18–33). The majority of participants reported little or no musical experience (<1 year). Those who were musically trained ($n = 9$) reported 6.67 years of formal training (range 1–16) and 10.11 years of overall performance experience (range 2–34) on average. Six of them had piano training: 5 years of formal training (range 1–10) and 6.17 years of overall experience (range 1–14) on average. One participant reported having absolute pitch; no participant reported hearing problems or motor dysfunction (though all were asked).

Apparatus

Auditory feedback manipulations and the collection of onset time data (from taps and feedback) were carried out using the FTAP software program (Finney, 2001). Participants used a Roland SPD-6 percussion pad for tapping. They 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 a Roland RD-700 digital piano.

Motion capture data, from a single marker placed on the fingernail of the index finger, were collected using a Visualeyez single-tracker active motion capture system (Phoenix Technologies, Burnaby, BC).

Conditions

The experiment consisted of a repeated measures design with the single factor delay length. Delays varied from 0% (normal) to 88% in steps of 12.5% (rounded to the nearest percent) which generated eight delay conditions.[1] Delays were based on a running average of inter-response intervals (IRIs, see *Procedure*). These conditions were repeated in four consecutive blocks of trials in which participants experienced all eight conditions in one block before proceeding to the next block. Trials were arranged in two random orders with the constraints that delay length did not change in the same direction across more than three consecutive trials (e.g., if three trials included delays of 50%, 68%, and 75%, the next condition could not be 88%), and the first trial in the experiment was always normal feedback. The two random orders of trials were counterbalanced across participants.

Procedure

At the beginning of the session, participants were trained in synchronization tapping. Participants were told to tap with the index finger of their right hand in the center of drum pad #2 (the upper middle section of a 2 × 3 grid on the surface of the drum pad) and to rotate at the elbow, keeping their wrist and finger stationary. Then participants practiced synchronizing with the metronome at a period of 500 ms (120 beats per minute), until the experimenter was convinced that the participant was synchronizing to the best of their ability. Then participants were familiarized with DAF by tapping with a delay of 25% and finally they completed a practice trial (again with a 25% delay) to experience the transition from synchronization to continuation (see below) before going on to the full experiment.

Trial structures followed the synchronization-continuation paradigm (Stevens, 1886; Wing & Kristofferson, 1973); altered feedback conditions occurred during the continuation phase. First the metronome sounded (at a period of 500 ms) and participants were instructed to synchronize after hearing the first four metronome sounds. During synchronization, participants heard normal (synchronous) auditory feedback. After 16 synchronization taps, 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 after which feedback ceased. During normal feedback conditions, feedback events were coincident with taps. During trials with delays, FTAP maintained a running average of the previous two IRIs. After each keypress, FTAP delayed the presentation of feedback by a percentage of this predicted IRI length.

Data Analysis

Keypress times were extracted from the MIDI data stream using FTAP and were used to compute IRIs via the time elapsed between successive keypresses (in ms). IRIs outside a boundary of +/− 400 ms surrounding the target IRI (500 ms) were considered outliers and were not included; such extreme changes are rare in performance of isochronous sequences with DAF (cf. Finney, 1999) and more likely reflect "double taps" (IRIs < 100 ms) or missed taps (IRIs > 900 ms) which were found to happen occasionally with the response device. On average, 6% of IRIs per trial were considered outliers using this standard.

The two measures of disruption we used focused on overall production rate and the variability of IRIs during continuation (when delays might be present). Overall rate was measured as the difference in mean IRI during continuation from the mean IRI maintained during synchronization: IRI-diff scores (IRI-diff = $M_{continuation} - M_{synchronization}$). A positive difference score indicated slowing during continuation and a negative score indicated speeding of IRIs. The variability of IRI timing during continuation was assessed using coefficients of variation, or CV, which is the ratio of the standard deviation of IRIs to mean IRI during continuation ($CV = S_{IRI}/M_{IRI}$). CV scores control for the standard tendency for variability to increase with mean IRI (Wing & Kristofferson, 1973). This advantage is particularly important in the current study as we wish to assess the effect of DAF on timing variability independently of its effect on overall rate.

Motion data were obtained from the VZsoft software program (Phoenix Technologies, Burnaby, BC) which collected data from the Visualeyez tracker at a sampling period of 10 ms (100 Hz). Motion data were collected in three dimensions; however, we focused only on the vertical dimension (*Z* plane) as any movement along the other planes was not directly related to the tapping task. Motion data for each trial were aligned with FTAP data offline based on minimizing the following function:

$$Y_a = \sum_{i}^{N} (Z_{t(i)-a})/N$$

We begin with a vector of times associated with MIDI keypress events as recorded by FTAP: $t = \{t(1), t(2), \ldots, t(i), \ldots, t(N)\}$. Each of these times is associated with a finger height, *Z*, recorded by motion capture. Because the timestamps recorded by MIDI and by motion capture were not always synchronized, the initial vector of MIDI keypress times did not always appropriately match keypresses recorded by motion capture. Thus the parameter, *a,* was used to shift the times in the MIDI time vector, thereby shifting the times associated with finger heights in the motion data. When the mean finger height across values of *t* is minimal the optimal aligning of vectors has been achieved. The minimization routine we used was an exhaustive search of all possible values of *a*; in instances where multiple values of *a* led to equivalent values of *Y* we chose the lowest value of *a.* Alignment of motion with MIDI data for best fitting values of *a* were then visually inspected for accuracy; manual re-adjustments were needed for four trials from one participant. In all other cases, the automatic adjustment described above provided a good match between MIDI and motion data.

[1] MIDI devices typically include transmission delays that are short (on the order of 20 ms), unnoticeable and do not have an appreciable effect on production. It can be assumed that such transmission delays are present in all DAF conditions here and function as a constant.

After identifying the best value of *a*, kinematic variables associated with feedback onset times (also taken from FTAP) were calculated. Kinematic data were computed in two ways, based on the data (numerically) and from best fitting functions derived from functional data analysis (FDA, Ramsay & Silverman, 2005). Finger position was extracted from the raw movement data (from the z plane). For analyses that used position at time of DAF as a predictor, finger positions were normalized to be a proportion of the total range of movement within a single IRI. Numerical estimates for finger velocity (Z') were obtained using the slope formed by the two position samples surrounding the time of feedback onset (three values in all). This numerical procedure converged well with derivation of Z' from continuous FDA functions described below.

Functional data analysis involves fitting a set of connected functions, known as basis functions, to the data at regular intervals. The function used here was a 6th order B-spline function. Best-fitting functions are determined based both on least-squares estimation and on smoothness (minimization of variability in the 2nd derivative). A free parameter, λ, determines how much weight is given to least-squares versus smoothness. Based on the use of both goodness-of-fit metrics and visual inspection, a lambda of 10^{-18} was used here as in other research (Goebl & Palmer, 2008). FDA is advantageous because in addition to smoothing the data it allows one to generate estimates of velocity and higher derivatives directly from basis functions. Visual inspection of FDA estimates indicated high similarity to the original data (and numerical estimates of higher derivatives), as did goodness-of-fit measures.

Results

DAF Disruption of Inter-Response Timing

IRI-diff scores (continuation – synchronization, see *Data Analysis*) are shown for each delay condition, averaged across repetition and participant, in Figure 1. The effect of delay length was significant, $F(7, 161) = 24.17$, $MSE = 344.48$, $p < .01$, $\eta_p^2 = 0.54$. The graph shows that as delays length increased from 0 to 38%, IRIs slowed. Then the pattern reversed, crossing zero at a delay of approximately 63%, and delays longer than 63% led to shortening of IRIs. These observations were affirmed via post-hoc comparisons (Tukey's HSD, $\alpha = .05$), which suggested that delays between 25% and 50% of IRIs significantly slowed timing, delays longer than 63% significantly sped timing, while delays of 63% (and 13%) did not significantly influence timing.[2]

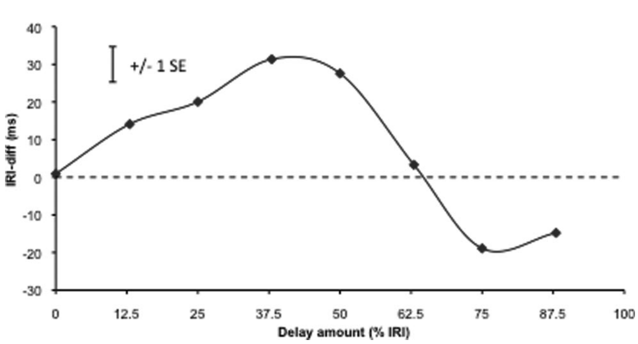

Figure 1. The effect of delay length (in % inter-response interval, IRI) on IRI-diff scores in Experiment 1. Error bars represent +/− 1SE. The dashed line highlights the zero crossing on the ordinate.

The "disruptive" effect of DAF on timing has most commonly been measured using production rate, as in the analysis above. However, DAF also influences the variability of IRIs (Pfordresher & Palmer, 2002). The relationship between DAF length and the variability of IRIs was assessed using coefficients of variation, or CV (see *Data Analysis*). Results are shown in Figure 2. As can be seen, CVs were influenced reliably by DAF, $F(7, 161) = 10.91$, $MSE < 0.001$, $p < .01$, $\eta_p^2 = 0.32$. The relationship, however, is different from that found for IRI-differences. Whereas production rate at first slowed down and then sped up as DAF changed, CVs were at first uninfluenced and then increased by DAF. This observation was verified by post-hoc tests. Delays greater than 50% all differed reliably from normal feedback whereas the remaining conditions did not differ. Interestingly, the first condition (as DAF increases) yielding a significant change in CVs was also the condition just prior to the zero-crossing for IRI-differences. Thus the disruptive effect of DAF on timing depends on what measure of timing one uses. The correlation between IRI differences and CVs was negative but fell short of significance, $r(6) = -.54$.[3]

DAF and Finger Trajectories

A major aim of this research was to determine whether the effect of DAF on IRI timing is linked to the state of the movement trajectory when DAF occurs. In other words, we sought to determine whether movement patterns constitute a source of information that the performer uses when coordinating perception and action. In order to test this relationship, it is important to first describe the movement pattern found within each delay condition. It may be the case that DAF causes alterations to the overall shape of the trajectory. Such a result would suggest that people adaptively alter their movement kinematics in response to DAF, which is plausible given the salience of DAF (cf. Wing. 1977).

We analyzed differences in finger trajectories between taps after normalizing IRIs to a common duration, with estimates of trajectories based on Functional Data Analysis (see *Data Analysis* for more details). Figure 3 shows examples contrasting normal feedback with two DAF conditions: delays of 38% (which led to greatest slowing) and 75% (which led to greatest speeding). Each data series represents the mean trajectory for each delay condition; paired t-tests were computed separately for contrasts between each DAF condition and normal feedback using a Bonferroni correction ($\alpha = .007$, assuming all seven possible contrasts). Asterisks highlight samples for which a significant contrast was identified. As can be seen, differences were found in the magnitude of maximal

[2] Results from other data sets suggest that a delay that is 100% of IRIs would not influence performance timing, although it may influence accuracy in more complex sequence production tasks such as melody production (e.g., Pfordresher, 2003).

[3] All bivariate correlations were confirmed by non-parametric Spearman's rho. In addition, correlations and regressions on mean data (averaged across participants and trials) were confirmed by analyses performed at the level of individual trial.

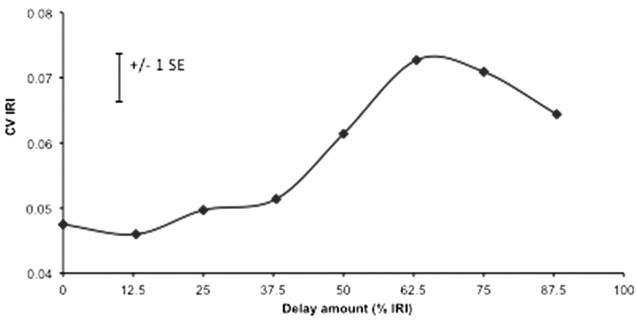

Figure 2. The effect of delay length (in % inter-response interval, IRI) on CV scores in Experiment 1. Error bars represent +/− 1SE.

amplitude. The 38% DAF condition (associated with slowing, Panel A) elicited a higher peak position of the finger than normal feedback. By contrast, the 75% DAF condition (associated with speeding, Panel B) was not associated with a comparable reduction in peak height. With respect to velocity, both DAF conditions led to increases in maximum upward and downward velocities, though these differences did not reach significance. Importantly, these plots suggest that the relative timing of kinematic landmarks (peaks and valleys) was invariant across feedback conditions, but that DAF may have influenced the magnitudes of these peaks and valleys. We next turn to an analysis that addressed this possibility across all conditions.

Table 1 shows values for kinematic landmarks—maximum position, maximum upward velocity, and maximum downward velocity—across all feedback conditions. The relative timing of landmarks within IRIs did not differ across conditions for any of the kinematic variables; thus the relative time of each landmark is shown averaged across feedback conditions below each column (time is expressed as a proportion of the IRI). As can be seen, peak position occurred at close to two-thirds of the IRI (cf. Balasubramaniam, Wing, & Daffertshofer, 2004) with maximum upward and downward velocities preceding and following the position peak, respectively.[4]

There was a significant effect of feedback condition on maximum finger position, $F(7, 161) = 4.71$, $MSE = 43.301$, $p < .01$, $\eta_p^2 = 0.17$. Post-hoc tests (Tukey's HSD, $\alpha = .05$) revealed that DAF ranging from 25% to 50% yielded significantly higher peak positions than normal feedback, while the rest did not differ. Thus, slowing by DAF was associated with increased movement amplitudes, but speeding by DAF was not associated with decreased amplitude (cf. Figure 3).

DAF increased peak upward velocity in most DAF conditions relative to normal feedback, $F(7, 161) = 2.79$, $MSE = 0.002$, $p < .01$, $\eta_p^2 = 0.11$. Post-hoc tests suggested that the 25%, 50%, 63%, and 75% conditions significantly elevated maximum upward velocity. Thus for maximum position increased height was associated with delays causing slowing, whereas increases in velocity were associated with DAF irrespective of slowing versus speeding. Finally, DAF did not significantly influence the magnitude of downward velocities ($p = .09$). According to planned comparisons, only the contrast between the 50% DAF condition and normal was significant given the correction, though all other conditions would be significant without the correction ($p < .05$ for each). Overall, these results suggest a weak effect, if any, of DAF on minimum velocity, and like maximum velocity the effect did not depend on whether DAF sped up or slowed down IRIs.

It is important to note from these results that DAF did not alter the relative timing of peaks and valleys in finger trajectories. This was true of all conditions; analyses of variance (ANOVAs) on the timing of peak finger height, peak velocity, and minimum velocity all failed to yield a significant effect of delay condition. Thus it can be said that the overall shape of the trajectory was invariant across delay conditions; that is, the differences we found were quantitative rather than qualitative.

Predicting Disruption from Movement Variables

We now consider movement variables (Z and Z′) that were associated with the DAF onsets in different delay conditions. Figure 4 shows finger heights (Figure 4A) and velocities (Figure 4B) that were associated with DAF onsets across conditions. Because finger trajectories did not change qualitatively within different DAF conditions, these plots resemble plots of finger trajectories shown in Figure 3. These analyses establish that different DAF onset times were associated with reliable differences in kinematic states. Figure 4A shows reliable differences in finger height associated with the timing of DAF onsets, $F(7, 161) = 265.52$, $MSE = .011$, $p < .01$, $\eta_p^2 = 0.92$. As can be seen, finger height was highest for delays of 63% and was lower at the time of delays surrounding this peak. DAF length was also associated with reliable differences in finger velocity at the time of DAF onset, $F(7, 161) = 97.63$, $MSE = 2.49$, $p < .01$, $\eta_p^2 = 0.81$, as shown in Figure 4B. Shorter delays were associated with positive velocities—the finger's upward-swing phase—and longer delays were associated with negative velocities—the downswing phase. Now we turn to the critical point: To what degree do the values of kinematic variables at the time of DAF predict the effect that DAF has on IRI timing?

Figure 5 plots the relationship between kinematic variables associated with DAF onsets and the effect of DAF on production rate (IRI-diff scores). Figure 5A plots finger position. The continuous line connects successive increases in delay length, with the point associated with normal feedback shown on the far left. As can be seen, the relationship forms an oval shape and does not suggest that IRI differences are predicted by finger position, $r(7) = 0.03$. However, finger velocity at feedback onset, shown in Figure 5B (normal feedback is shown at the intersection of the cross-hairs), did predict IRI differences, $r(6) = .92$, $p < .02$. The finger's velocity at the time of DAF thus predicts 85% of the variability in IRI-diff scores. Fits of higher-order polynomial (non-linear) regressions provided a somewhat better fit (88% variance for second-order, 95% for third-order); however, analyses of semi-partial coefficients suggested that only the linear component contributed independently to the prediction. On an individual level, the data of 20 out of 24 participants yielded a significant positive relationship between finger velocity and IRI differences. The major result listed here held on a categorical level too; on 71% of all

[4] Note that the values in Table 1 are slightly greater than peak values shown in Figure 3 due to the fact that means in Table 1 result from aligning the timing of peak position across trials.

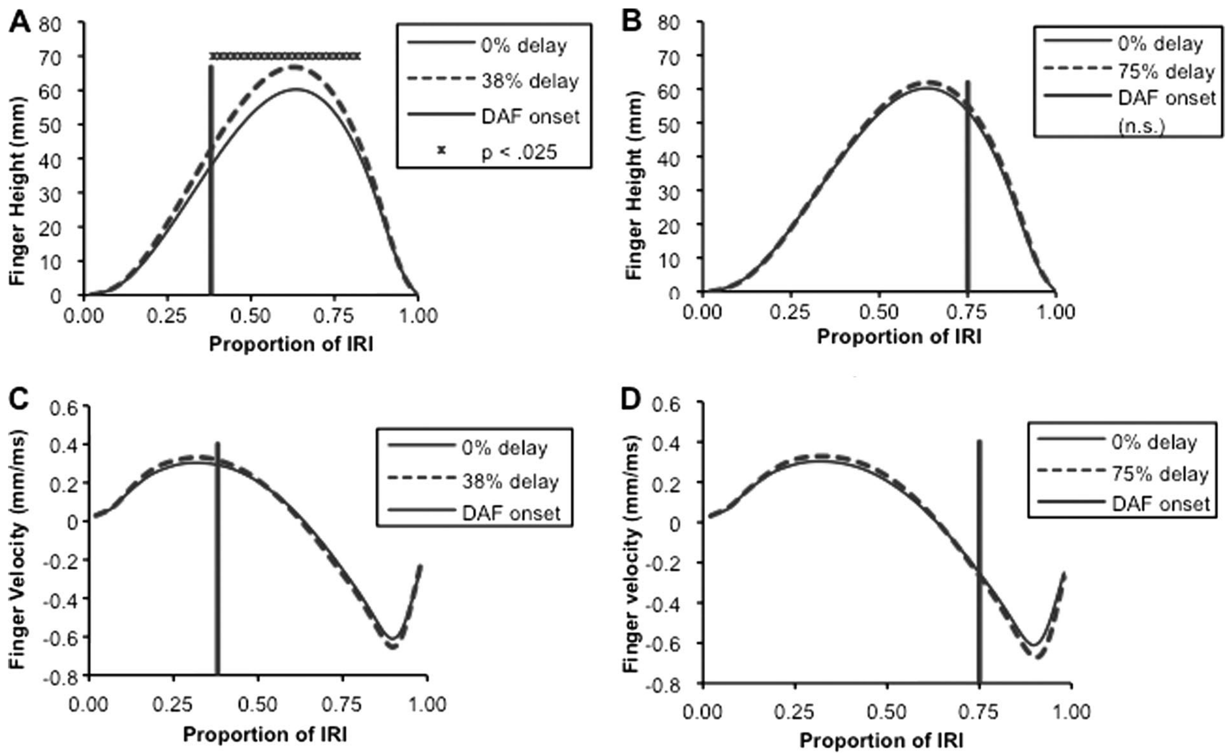

Figure 3. Mean finger trajectories for the Z plane (height) across delay conditions in Experiment 1 after standardizing IRIs. Plots show contrasts between normal feedback and two selected DAF conditions, 38% (plots A and C) and 75% (plots B and D). Plots A and B show finger position, plots C and D show velocity. Solid vertical lines highlight the relative timing of DAF onsets and asterisks above trajectories highlight samples associated with significant contrasts (α = .025, adjusting for multiple comparisons).

combinations of trial and participant (n = 764) the finger velocity associated with DAF had the same sign as the IRI difference score.

The plots in Figure 6 focus on timing variability (CV IRI). Figure 6A shows the relationship between finger position and CVs (normal feedback is again the point to the far left). In contrast with findings for IRI differences, this relationship was significant, $r(6) = .81$, $p < .01$ (65% of variance), whereas the relationship between finger velocity and CV, shown in Figure 6B (normal feedback is positioned at X = 0), was negative and fell short of significance, $r(6) = -.63$. With respect to position, timing variability increased if DAF occurred at higher finger positions, and was less if DAF occurred at low finger positions (e.g., normal feedback, which is the point to the far left). Fits of higher-order polynomial (nonlinear) regressions provided only slightly better fits (66% variance for second-order, 69% for third-order); moreover, because the additional parameters decreased the degrees of freedom for the fits, these higher-order fits were not significant. With respect to velocity, we found a (nonsignificant) tendency for CVs to be greater when DAF occurred at negative velocities (the downswing phase) than when it occurred at positive velocities (upswing phase).

Given that our sample included various levels of musical training, one might wonder if the data shown above better characterize either musicians or non-musicians. We divided our sample into two groups, one reporting no musical training, the other reporting some musical training (including the participant reporting only 3 months). The two groups' pattern of data did not differ for any of the variables involved (IRI-diff, position, velocity). Moreover, the relationship between finger velocity at the time of DAF onset and IRI differences was significant for both groups, although the relationship was larger for nonmusicians ($r^2 = 0.87$) than for musicians ($r^2 = 0.65$).

Discussion

In Experiment 1 we found that the effect of DAF on timing of mean IRIs is not unidirectional. Instead, DAF either slowed down or sped up production rate, depending on the length of the delay relative to IRIs. The pattern of disruption across delays formed a roughly sinusoidal curve, with maximal slowing of delays around 50% of IRIs, a negative-going zero-crossing at delays around 63% of IRIs, and speeding up for delays around 73% of IRIs. This finding is similar to what has been found in synchronization tasks when participants are presented with periodic distracter sequences that are phase shifted relative to the target sequence (Repp, 2003, 2004). Thus the effects found in Experiment 1 need not reflect the effect of "feedback" so much as the disruptive effects of auditory rhythms that interfere with the timing of actions (cf. Howell et al., 1983).

At the same time, we found a very different effect of DAF on the variability of produced timing, with a peak in variability around delays of 63%, a condition that did not influence rate. In

Table 1
Means (SE) for Maximum Finger Height, Maximum Finger Velocity, and Minimum Finger Velocity Across Delay Conditions. The Relative Time of These Values Within IRIs (Given as a Proportion of IRI) Is Also Listed

Delay	Maximum position (mm)	Maximum upward velocity (mm/ms)	Maximum downward velocity (mm/ms)
0%	64.3 (4.9)	0.40 (0.03)	−0.76 (0.05)
13%	69.6 (5.1)	0.43 (0.03)	−0.84 (0.07)
25%	71.2 (4.9)	0.44 (0.03)	−0.82 (0.06)
38%	70.4 (4.6)	0.43 (0.03)	−0.81 (0.05)
50%	72.5 (4.9)	0.45 (0.03)	−0.84 (0.06)
63%	68.7 (5.0)	0.44 (0.03)	−0.82 (0.05)
75%	65.9 (4.8)	0.44 (0.03)	−0.83 (0.06)
88%	65.8 (4.9)	0.43 (0.03)	−0.82 (0.06)
Timing*	0.65 (0.01)	0.34 (0.02)	0.93 (< 0.00)

* Timing units are expressed as a proportion of the IRI. For each Kinematic measure, timing differences for each condition were within one standard error (no significant differences) and so means across delay conditions are given.

addition, different movement variables best predicted the effects of DAF on rate of timing (mean IRI) and the precision of timing (CV of IRI). Whereas the effect on rate was best predicted by finger velocity, the effect on precision was best predicted by finger position.

It is important to point out that the results of Experiment 1, even disregarding correlations with movement variables, are difficult to resolve with an account of disruption based strictly on the relative phase of tone onsets within IRIs. According to such an account, feedback onsets may exert an attracting effect on taps, thereby shifting timing of the closest tap in a way that increases the proximity of feedback to taps (for a representative model, see Large & Jones, 1999). Such an account would predict that the point at which disruption shifts would be the midpoint of the IRI. However, the data from Experiment 1 clearly show the reversal to be later than this midpoint and, more important, at a point that is consistent with movement patterns. Likewise, similarly asymmetric effects of periodic distractors on synchronization (Repp, 2003, 2004), with early distractors leading to larger phase shifts than late distractors may likewise reflect asymmetries in movement patterns.

However, there is an inherent limitation in Experiment 1 given that the link between the effect of DAF and movement kinematics is correlational. Thus it is impossible to fully distinguish the effect of relative phase from the effects of movement variables. In Experiment 2 we ran a follow-up study that attempted to address this issue by having participants alter their movement trajectories while tapping.

Experiment 2

In Experiment 2 participants were instructed to tap in ways that varied the timing of peak finger height within the IRI. Three tapping regimes were used, one in which the target peak time was 40% of the IRI, one in which it was 63%, and one in which it was 80%. These target times were selected based on the fact that in Experiment 1 delays coinciding approximately with these time points yielded maximal slowing (40%), no effect (63%), and maximal speeding (80%) effects on timing. Participants were trained to adopt these regimes and then completed three blocks of trials, one for each tapping regime. During each block of trials participants experienced all the DAF conditions used in Experiment 1. Because Experiment 2 was designed to assess the primary implications of Experiment 1 in an experimental framework, we focus on the primary data analyses from Experiment 1: The relationship between IRI-diff scores and finger velocity at the time of DAF, and the relationship between CV scores and finger height at time of DAF. If, as we have claimed, disruption of IRI timing is attributable to movement states when DAF occurs, then changes in the temporal pattern of the movement trajectory should be associated with commensurate changes in the effect of DAF on IRI timing.

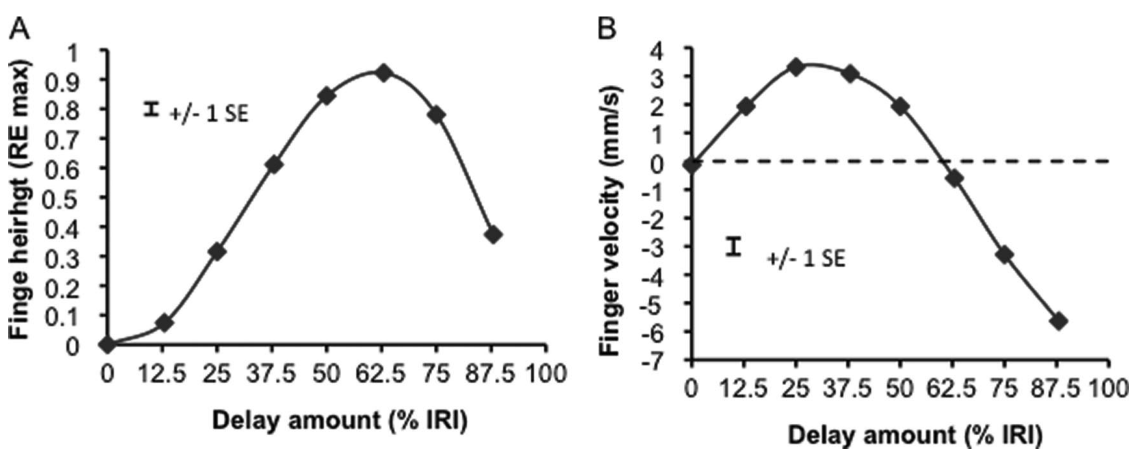

Figure 4. Mean movement state associated with DAF onsets across feedback conditions in Experiment 1: (A) finger position, Z, expressed as proportion of peak within the IRI (Zero indicates surface contact, 1 indicates peak height) and (B) finger velocity (Z′). Error bars represent +/− 1 SE.

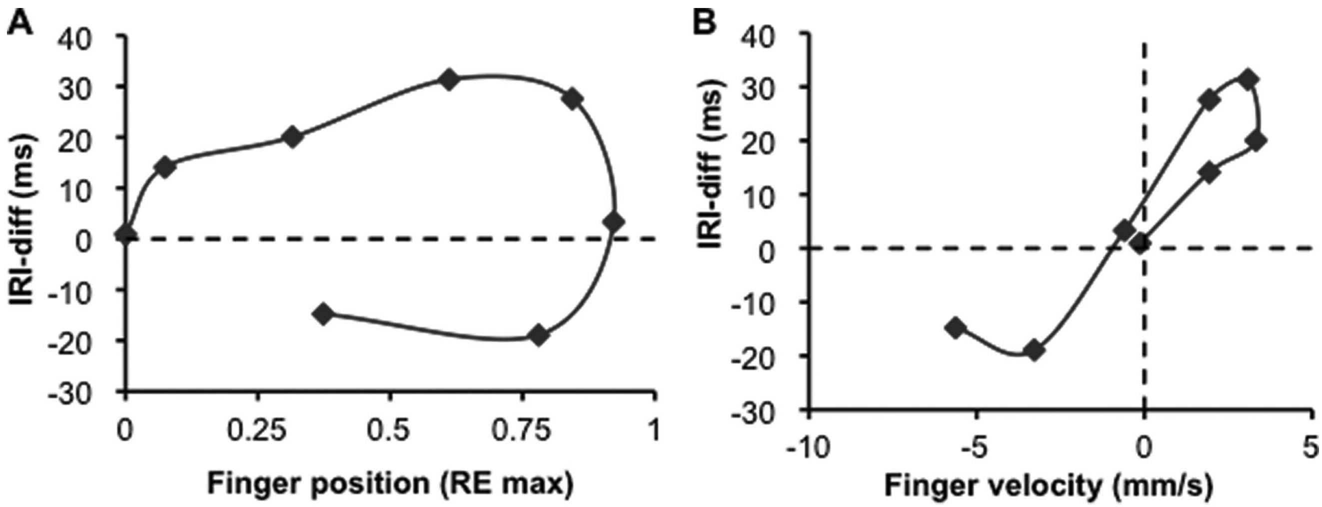

Figure 5. (A) The relationship between finger position (as proportion of maximum height) and IRI differences in Experiment 1. (B) The relationship between finger velocity and IRI differences. Dashed lines highlight zero crossings.

Method

Participants

Twenty-two participants volunteered to take part in this experiment; 19 were volunteers from the Introduction to Psychology participant pool and the remaining three were lab personnel. These remaining three were incorporated in the sample after it became clear that many participants were unable to perform the tapping task accurately. From the 22 original participants we retained only those participants who were judged by the experimenter as being able to vary their finger trajectories during learning trials (which was later confirmed by visually inspecting movement data). This resulted in a final sample of 10 right-handed participants (45% of the original sample, two female, mean age = 21, range 19-26). Most participants had modest amounts of musical training (*M* years of training summed across instruments = 6, range 0-16, with two participants reporting no training). No participants reported having absolute pitch, hearing disorders, or disorders of motor function.

Apparatus and Conditions

The apparatus for collecting data was identical to that of Experiment 1, with the exception that participants tapped on one key of an electronic keyboard rather than the drum pad. This change was introduced because we found that the drum pad required considerable force to properly register a tap (even when set to its

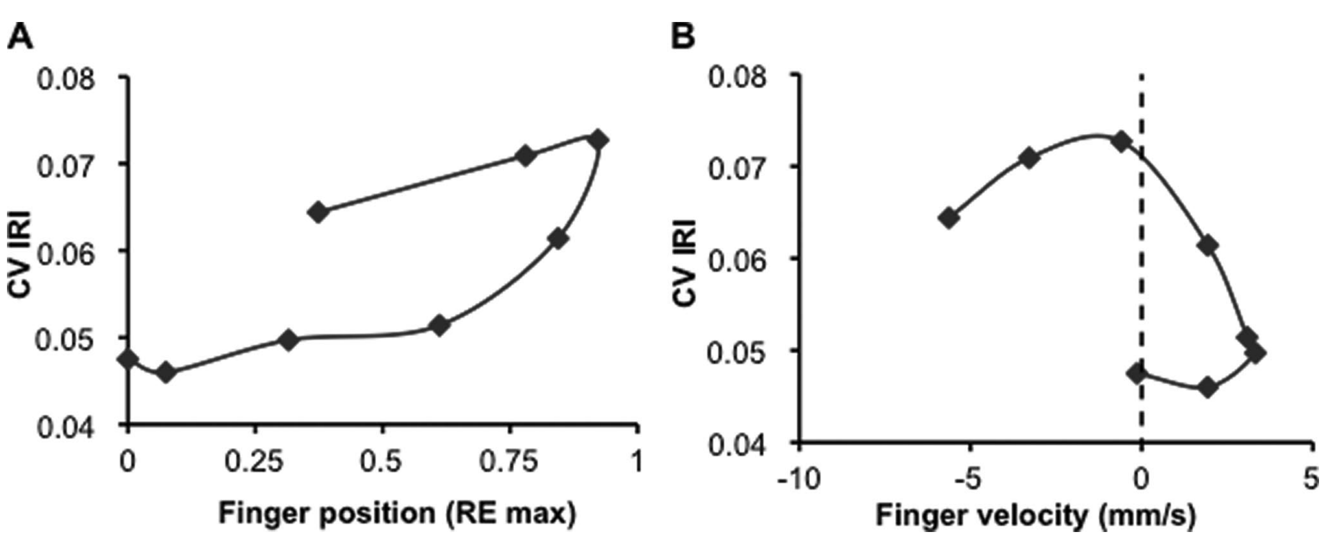

Figure 6. (A) The relationship between finger position and CV IRI in Experiment 1. (B) The relationship between finger velocity and CV IRI. The dashed line highlights the abscissa zero crossing.

"sensitive" mode); thus the use of a keyboard reduced the risk of hand fatigue.

Experiment 2 included the factor feedback condition (as in Experiment 1) plus the additional factor tapping regime. In different blocks of trials, participants were instructed to tap in such a way that the peak height of the finger was positioned at different times within the IRI: 40%, 63%, or 80%. There were thus 24 conditions in Experiment 2 (eight feedback conditions × three tapping regimes). In order to limit the total time of the experiment, the number of repetitions for each condition in the experiment was reduced from 4 to 2. Four between-participant order conditions resulted from combining two counterbalancing orders of tapping regimes with two random orders of delay conditions within blocks. Each of the counterbalancing orders began with the 63% tapping regime because this was considered to most closely resemble participants' spontaneous tapping (based on Experiment 1); counterbalancing conditions thus differed with respect to whether the 40% preceded the 80% regime or vice-versa.

Presentation of the metronome during the synchronization phase of experimental trials was also altered in order to facilitate participants' ability to maintain the prescribed tapping regime. Metronome clicks were presented as lower-pitched piano tones (C3) in comparison to interleaved higher-pitched tones (C4) that represented the ideal timing of the participants' peak finger height. Additional auditory stimuli were designed to help participants learn tapping regimes at the beginning of an experimental block. These stimuli featured a recurring frequency sweep in which the minimum of the modulation frequency was positioned in synchrony with metronome onsets (represented as clicks in the stimulus). In between these minima, the frequency would sweep up and down linearly and would reach its peak at a time matching the target timing of the finger peak.

Procedure

At the beginning of the session participants were given a general description of the task and instructions on tapping, as in Experiment 1, and a single marker was attached to their index finger. Then participants were trained to synchronize with a metronome and were recorded doing so. This recording functioned as a measure of participants' spontaneous movement trajectories. Then participants were trained to tap according to the 63% regime. Participants were presented with the auditory training stimulus for this regime (described earlier) and were told that the changing pitch represented the way in which the finger should be moved during a trial. In order to facilitate performance, participants were also shown motion capture output associated with the marker positioned on their index finger. This output was represented as a single red dot on a computer screen positioned in front of the participant. As they moved their finger they could see the single red dot moving on the screen, and match the movement of this stimulus to changes in the frequency modulated auditory stimulus. Participants were allowed to practice doing this for as long as they wished. Following this training phase the computer screen in front of the participant was switched off and they no longer received visual feedback from motion capture until the training phase for the next block.

Participants then completed a practice trial and a block of experimental trials using the 63% tapping regime. These trials were identical to Experiment 1 except that the metronome pattern during synchronization phases was designed to remind participants of the tapping regime, as described earlier. Following this first block of trials participants were given a break followed by two more trials for each of the other two tapping regimes.

Results

Data from Experiment 2 were analyzed in the same manner as were the data in Experiment 1, after incorporating the additional factor tapping regime. As mentioned before, participants found it difficult to maintain the prescribed trajectories, and even the subset of overall best-performing participants was not able to maintain the intended regime on every trial. In light of the apparent difficulty of the task we adopted the following approach to data analysis. Preliminary investigation of the trials suggested that although participants could not in general adopt the prescribed regime they were often able to differentiate the very early (40%) and very late (80%) trajectories by positioning peak finger height relatively early or late within the IRI. Furthermore, participants maintained a consistent finger trajectory within trials though they would often deviate from these trajectories across different trials. Thus we selected those trials on which the intention to tap "early" was borne out in finger trajectories for which peak height, on average, occurred earlier than 63% of the way through the IRI, as well as trials on which the intention to tap "late" led to peak heights later than 63% through the IRI. Sixty-four percent of all trials met this criterion. Chi square analyses verified that the number of acceptable trials did not vary reliably as a function of delay length or intended tapping regime. Thus, the analyses reported reflect a subset of best trials for a subset of the total participants ran. We felt this restriction was necessary based on the difficulty of the task. It is important to point out that our restrictions of the participants and trials used for analyses do not reflect a bias toward our hypothesis; they are only based on the ability to perform the task. For each participant, missing values (i.e. trials that did not match the criterion) were replaced with the mean value for all other participants for that combination of tapping regime and delay length.

The mean finger trajectories for this subset of the data are shown to the right of Figure 7. As can be seen the data for finger height (7A), tapping trajectories are in qualitative agreement with instructions, leading to a significant tapping regime × delay length interaction, $F(7, 63) = 11.77$, $MSE = 0.012$, $p < .01, \eta_p^2 = 0.57$, in addition to a main effect of feedback, $F(7, 63) = 144.27$, $MSE = 0.012$, $p < .01, \eta_p^2 = 0.94$, and a marginal (though of modest effect size) main effect of tapping regime ($p = .06$, $\eta_p^2 = 0.34$). As can be seen, peak finger heights occurred later in the trajectory for the 80% tapping regime than the 40% tapping regime, though neither data set perfectly reflected the intended timing. This result is of course to be expected based on how the data were selected. By contrast, the regime × feedback interaction for finger velocities (7B) was marginally significant ($p = .06, \eta_p^2 = 0.19$), though the significant main effect of delay length, $F(7, 63) = 44.85$, $MSE = 163.20$, $p < .01, \eta_p^2 = 0.83$, replicated what was found in Experiment 1 (there was no main effect of regime, $p > .10, \eta_p^2 = 0.13$). Moreover, it is important to note that patterns of change in finer velocity across the two tapping regimes did not follow directly from change in finger position, which would have

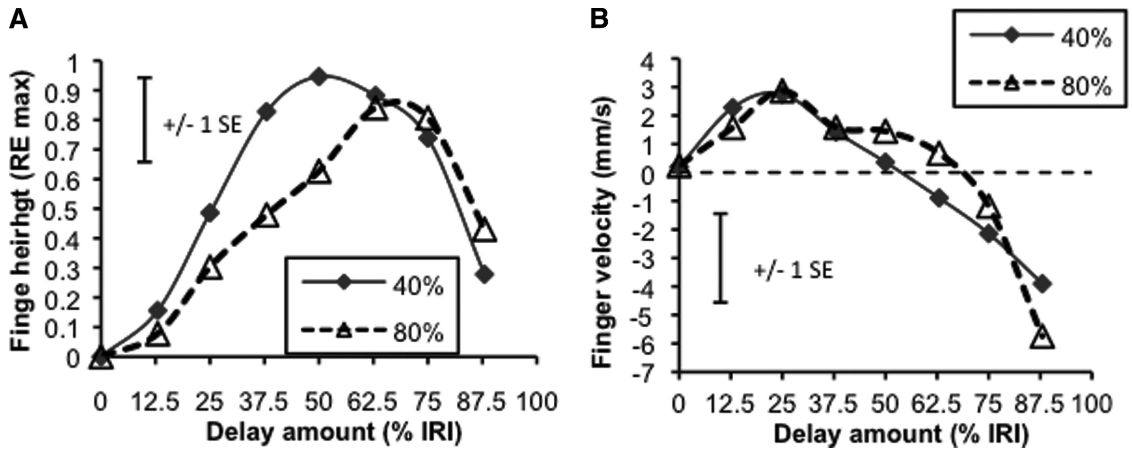

Figure 7. Mean movement state associated with DAF onsets across feedback conditions and tapping regime in Experiment 2 for trials that were most representative of the 40% and 80% tapping regimes (see text for details): (A) finger position, Z, expressed as proportion of peak within the IRI (Zero indicates surface contact, 1 indicates peak height) and (B) finger velocity (Z′). Error bars represent +/− 1 SE, averaged across feedback condition and tapping regime.

led to an earlier peak velocity for the 40% relative to the 80% tapping regime.

Figure 8A shows mean IRI-diff scores by tapping regime and feedback condition. The ANOVA on IRI-diff scores only yielded a main effect of delay length, $F(7, 63) = 7.9$, $MSE = 265.787$, $p < .01$, $\eta_p^2 = 0.47$. The overall effect of delay on IRI-diff scores was like that of Experiment 1, with delays smaller than 63% causing slowing and those higher causing speeding. By contrast, changes in tapping regime did not clearly yield the predicted effect, which would be an earlier peak in the function for the 40% relative to the 80% regime. The downward crossover occurred for longer delays when participants maintained the 80% than the 40% regime, but there was no clear difference in the delay leading to maximal slowing and, more to the point, the interaction was non-significant ($p > .50$, $\eta_p^2 = 0.07$). However, recall that patterns of finger velocity did not change reliably with the timing of peak finger height. In this context, it is worth noting that the relationship between finger velocity at the time of DAF and the effect of DAF on IRI-diff scores was significantly positive as in Experiment 1, $r(14) = .86$, $p < .01$. This relationship is shown in Figure 8B (normal feedback conditions are nearest to the intersection of crosshairs). Fits of higher-order polynomials suggested that a third-order function may provide a better fit (84% of the variance, relative to 74% by the linear fit), with the cubic component and linear components contributing independently to the variance; this result reflects the sigmoidal shape of the function shown in Figure 8B. Relationships were also reliable within each tapping regime, for 40%, $r(6) = .89$, for 80%, $r(6) = .91$, $p < .01$ for each. The relationship between finger height and IRI-diff scores was not reliable, $r(14) = -.14$, as in Experiment 1.

Next we turn to timing variability, measured by CVs. Recall that in Experiment 1, CVs for IRIs were predicted by finger height at the time of DAF rather than finger velocity. Figure 9A shows CV scores by tapping regime and delay length. The ANOVA yielded a significant main effect of delay length, $F(7, 63) = 6.22$, $MSE < .001$, $p < .01$, $\eta_p^2 = 0.41$ and a significant delay length × tapping regime interaction, $F(7, 63) = 2.28$, $MSE > .001$, $p < .05$, $\eta_p^2 = 0.20$, but no main effect of tapping regime ($p > .10$, $\eta_p^2 = 0.12$). As predicted, highest CVs were found for shorter delays while participants timed their peak finger height early in the IRI than when they timed their peak finger height late in the IRI. Post-hoc tests (Tukey's HSD, $\alpha = .05$) confirmed this interpretation; whereas in the 40% tapping regime, only the 50% delay condition yielded CVs higher than normal feedback, delay conditions elevating CVs for the 80% tapping regime were found for the 63% and 75% delay conditions.

Figure 9B plots the relationship between finger height at the time of DAF and CV scores, to test whether the qualitative match to our predictions holds when the data are assessed as a continuum. This relationship was strong and positive, $r(14) = .89$, $p < .01$; fits of higher-order polynomials did not increase the variance accounted for (65% for the linear fit). Correlations within each tapping regime were likewise reliable: for 40%, $r(6) = .92$, for 80%, $r(6) = .91$, $p < .01$ for each. Thus, although the different tapping regimes led to reliable differences in the functions relating DAF length to CV scores, these differences can be reconciled by taking into account differences in finger height at the time of DAF. This result is important in that it supports the idea that the state of the movement trajectory at the time of DAF determines the effect of DAF on IRI timing. As in Experiment 1, CV scores were not reliably predicted by finger velocities at the time of DAF, $r(14) = -.24$.

Finally, we assessed the discriminant validity of relationships between finger heights associated with DAF and the effect of DAF on CV scores. If finger height predicts the effect of DAF, then finger heights associated with one tapping regime should not predict (or should more weakly predict) the effect of DAF for the alternate tapping regime. The correlations between finger height and CV scores within each tapping regime were high and significant, as described above. By contrast the relationship between finger heights from one regime and CV scores from the other regime were relatively smaller, though still significant (at $p < .05$).

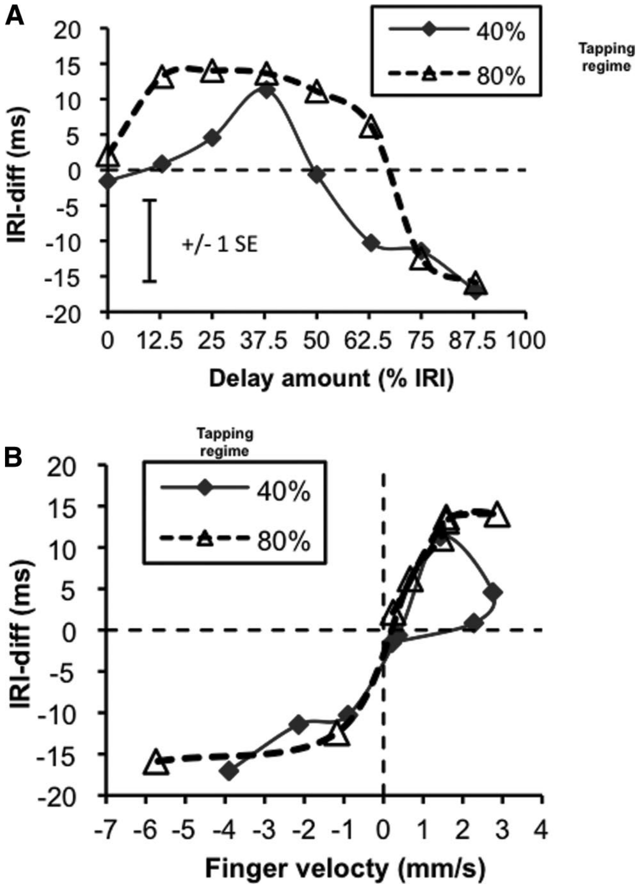

Figure 8. (A) The effect of delay length (in % inter-response interval, IRI) and tapping regime on IRI-diff scores in Experiment 2. The dashed line highlights the zero crossing on the ordinate. (B) The relationship between finger velocity and IRI-diff scores.

The correlation between finger heights for the 40% regime and CV scores for the 80% regime was $r(6) = .71$, and the correlation between finger heights for the 80% regime and CV scores for the 40% regime was $r(6) = .62$. We tested whether CV scores were better predicted by the appropriate than the inappropriate finger height vector using *t*-tests for dependent *r*'s (Cohen & Cohen, 1983, pp. 56–57). This test incorporates the correlation between the two position vectors, which was significant, $r(6) = .87$, $p < .01$. Both t-tests were significant, $t(5) = 2.62$, $p < .05$ for the 40% regime and $t(5) = 5.71$, $p < .01$ for the 80% regime. Thus finger position predicted CV patterns in a way that covaried reliably with different tapping regimes.

Discussion

In Experiment 2 we attempted to verify the implications of Experiment 1 by manipulating the timing of finger trajectories. The logic of Experiment 2 was that finger trajectories in which the timing of peak finger height was relatively early would lead to earlier peaks in the disruptive effect of DAF on IRI timing, with the converse holding for trajectories in which the timing of peak finger height was relatively late. This proved to be a very difficult task and in our analyses we were compelled to focus on a subset of the data that included the best trials from the best-performing participants. Even so, a critical margin of successful trials were identified in which participants were able to adopt the prescribed regime and our analyses focused on this subset of trials.

Overall the findings of Experiment 1 were replicated, in that changes to mean IRI timing were predicted by finger velocity at the time of DAF and changes to the variability of IRI timing were predicted by finger position. More important, the fact that participants were able to alter the timing of finger heights allowed us to address experimentally the relationship between IRI variability and finger height. This predicted relationship was upheld: When participants timed peak height earlier in the IRI, the peak in CVs for IRIs likewise moved earlier, with the converse holding when participants timed peak finger heights later in the IRI.

General Discussion

To our knowledge, this is the first study to evaluate the relationship between DAF disruption and movement kinematics quantitatively. In so doing we attempted to control—as far as possible—the relative timing of DAF onsets within produced IRIs during isochronous finger tapping. We measured finger move-

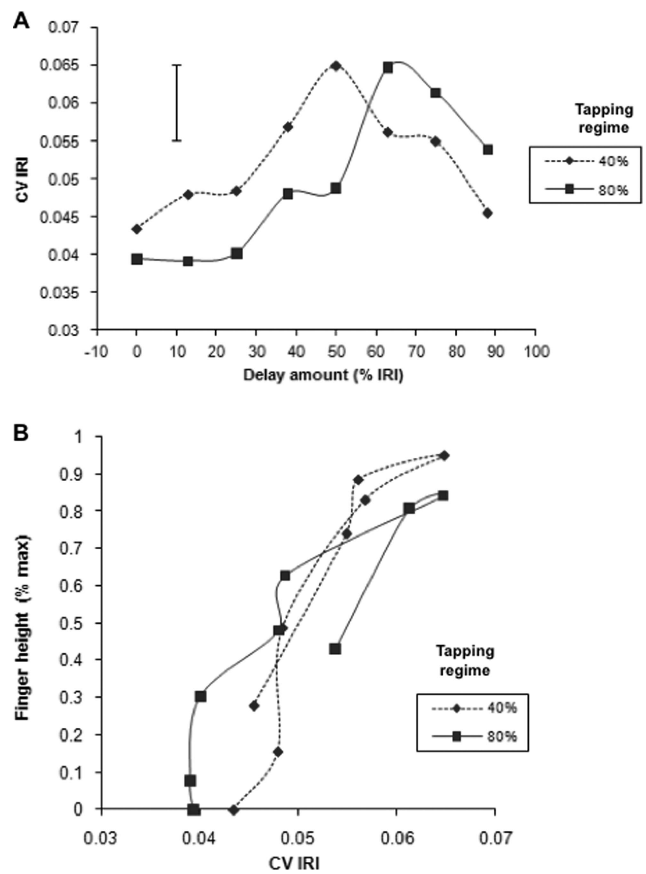

Figure 9. (A) The effect of delay length (in % inter-response interval, IRI) and tapping regime on CV scores in Experiment 2. Error bars represent +/− 1SE. (B) The relationship between finger position and CV scores.

ments during tapping in order to identify the values of kinematic variables at the time when a DAF onset occurs. The state of these variables at the time of DAF in turn predicted effect that DAF has on the timing of IRIs. In Experiment 2 we verified (for measures of timing variability) that intentional changes to the finger trajectory can alter the effect of DAF, providing further support for the idea that the effect of DAF is influenced by the state of the movement trajectory when feedback occurs.

Implications for Coordination of Perception and Action

DAF can be considered as a way of perturbing the naturally occurring synchrony between perception and action (cf. Pfordresher, 2006), with the effect of different delay lengths addressing the sensitivity of the perception/action system across different asynchronous coordination regimes. The deeper issue here is what kinds of movement information may cause perception and action to be coordinated in a way that is stable (leading to accurate and precise timing) or unstable (leading to breakdowns in timing).

A long-standing issue in the DAF literature has to do with whether the locus of DAF disruption is at the level of cognitive plans driving performance or in the execution of muscle movements. In this respect the current data are more supportive of movement-based theories (e.g., Howell et al., 1983) rather than theories that do not incorporate movement variables (e.g., MacKay, 1987). It is important to note, though, that it is unlikely that the coordination of perception and action is limited exclusively to either execution or planning. It is more likely that both components combine, and that different feedback alterations may selectively disrupt one or the other (Pfordresher, 2003, 2006).

A critical issue here is the functional significance of the movement variables that predict the effect of DAF on IRI timing. Here we draw on the aforementioned Theory of Event Coding (Hommel et al., 2001). Although this theory does not link perception and action at the level of movement, as noted before, the broader claim of this theory - that movements are encoded with respect to goals - is consistent with the current data. Consider movement velocity at the time of DAF, which was the best predictor of DAF's effect on production rate. In finger tapping, negative velocities are associated (by convention) with movement toward the goal (i.e., surface contact), whereas positive velocities are associated with movement away from the goal. Likewise, the onsets of sounds are usually associated with the completion of a goal. Thus, we suggest that when DAF co-occurs with the upswing phase of the finger (positive velocity) a conflict arises between the regulation of movement (away from the goal) and auditory information (suggesting the acquisition of a goal). The result of this conflict is slowing of IRIs. When DAF co-occurs with the downswing phase (negative velocity), auditory information complements the regulation of movement, and thus facilitates the approach to the goal, which speeds IRIs.

We found different results for measures of production rate and timing variability. As in other research (Pfordresher, 2003), the implication here is that altered feedback can differently affect different components of performance. Whereas DAF's effect on production rate was best predicted by finger velocity, its effect on timing variability was best predicted by finger position. Why? We suggest that the regulation of rate and precision in movement are sensitive to different kinds of information. Specifically, the maintenance of precise timing (low variability) requires that the producer maintain a certain standard, whether that standard is correct or not. Perturbations of this regularity may be greatest at points in the trajectory associated with uncertainty. We consider the peak in the fingers trajectory to be such a point, in that it marks a transition from one movement phase to the other. In kinematic terms the fingers peak defines the midpoint between phases of movement, even though it may not evenly bisect an IRI in time (Balasubramaniam et al., 2004). When DAF occurs at this point it may therefore be interpreted as antiphase coordination with actions. Other research suggests that antiphase constitutes a fixed but unstable point in coordination; though accuracy may not suffer (relative to in-phase coordination) precision may suffer (e.g., Amazeen, Amazeen, & Turvey, 1998; Kelso, 1995). A corollary implication of this discussion is that 'antiphase' coordination between DAF and actions may not be based on time, but based on movement. Previous studies that defined phase relationships based on time did not find strong evidence of an advantage or disadvantage for antiphase coordination (Pfordresher, 2003; Pfordresher & Palmer, 2002). The fact that this pattern differs from what one finds during antiphase synchronization with a metronome (for which precise antiphase coordination is more stable), suggests that coordination with an external source (a metronome) functions differently from coordination with one's own feedback.

We should also note that although the results suggest a strong role for movement in the effect of DAF, they do not entirely rule out a role for time. For instance, it is possible that tones preceding a tap are more perceptually salient than tones that follow a tap (Repp, 2003, 2004). Ultimately, time and movement are not easily separable, as movements are defined in part by time, and time and movement variables may both provide information about sensorimotor coordination. For instance, research on synchronization errors (the so-called negative mean asynchrony, Aschersleben & Prinz, 1995) has found that errors can be reduced when the metronome period is subdivided into smaller time intervals, and these subdivisions can be produced by an external stimulus (e.g., auditory rhythms) or by "submovements" (small fluctuations in finger height) that subdivide the overall movement trajectory (Wohlschläger & Koch, 2000).

Implications for the Effect of DAF

Why did the pattern of disruption in the current study differ from that found in past research? Many have claimed that the effect of DAF increases with delay lengths up to a delay around 200 ms and thereafter either remains fixed or decreases (see Finney, 1999, for a review). Our results differed in three critical respects.

First, the delay causing maximal slowing in the present study (the best evidence for "disruption") was much longer than 200 ms; slowest IRIs were for the 50% delay condition, which resulted on average in delays of 262 ms (+/− 3 ms *SE*). It has been noted before that maximally disruptive delays in music tend to be longer than those for speech (Gates, Bradshaw, & Nettleton, 1974) possibly due to fact that tones are typically longer than syllable durations (Howell et al., 1983). More recent research suggests that the length of delay associated with maximal disruption depends on tempo and that therefore disruption is best considered to result from relative phase rather than absolute time (Finney & Warren, 2002; Pfordresher & Benitez, 2007). Here we further link maximal disruption to movement kinematics.

Second, the function relating disruption to IRI timing was different for different measures of timing. Whereas the relationship between DAF and mean IRI was roughly sinusoidal, the relationship between DAF and the variability was not. More important, DAF lengths leading to maximal "disruption" differed across each measure. Delays that maximized the variability of IRIs had negligible effects on mean IRI. Thus, the conclusion one draws about delays that are "critical" (cf. MacKay, 1987) may depend on the measure of production one uses.

Third, the effect of DAF on mean IRI reversed for long delays. This has not been reported before to our knowledge although there have been occasional reports of participants who speed up with DAF (e.g., Gates et al., 1974). We suggest that this difference reflects the fact that our delay lengths were adapted to timing of production. It is worth noting that most studies of DAF involve the production of event sequences, which leads to more complex perception/action relationships (based on content) and the possibility of production errors. In such tasks, long delays may cause feedback to coincide with the next produced event, leading to a mismatch between the intended outcome of the produced action and the content of the feedback event. Such mismatches can lead to errors, as mentioned before, with consequent temporal disruptions (note that IRIs for errors are typically left out of timing analyses). Thus it is possible that in past research performers would initially respond to longer delays by speeding up slightly, but in so doing would bring about this kind of mismatch and thereby slow down timing.

Taken together, these points suggest that it is inappropriate to refer to the effect of DAF simply as "disruption." This term implies a unidirectional effect and does not leave room for the different patterns of data that we find for different measures of performance. Overall our data suggest that DAF's effect is complex and, in certain cases, bidirectional. It may be more appropriate to say that DAF imposes a phase perturbation on actions comparable to those seen in paradigms in which the timing of a single auditory event can perturb the timing of production (e.g., Repp, 2001, 2003; Repp & Keller, 2004; Wing, 1977).

Before closing, we wish to note that not all alterations of auditory feedback are likely to have effects that are related to movement. For instance, recent research has documented disruption of performance when feedback onsets coincide with contact times (piano key presses) but differ from the expected results of an action (one hears a different pitch than one expects; Pfordresher, 2003, 2005, 2008; Pfordresher & Palmer, 2006). Though these alterations may have some effects on timing (e.g., Keller & Repp, 2008), it is not clear how disruption would relate to fine-grained characteristics of movement trajectories as measured here. In particular, such manipulations always present DAF when the finger has contacted the piano key. Instead, this kind of disruption likely relates to the selection of actions. More generally, it has been suggested that different alterations of feedback may disrupt different levels of a planning hierarchy used to guide actions (Pfordresher, 2006). The current research was directed at the lowest level of this hierarchy, the regulation of contact times.

To summarize, the current study—we think—sheds light on some puzzling characteristics of the effect of DAF. First, we provide an explanation for why DAF can have strikingly different effects (e.g., speeding or slowing). These confusing results are resolved when one considers that DAF's effect is influenced both by the measure of disruption and the relationship between that characteristic of performance and movement states associated with feedback onsets. Second, we provide an explanation for why DAF causes disruption of timing, based on goal-related representations in a joint code for perception and action (cf. Hommel et al., 2001). That is, we suggest that DAF causes disruption because sounds are coded with respect to contact times, and so perturbs actions in a direction commensurate with that goal. More broadly, this research argues for paradigms that involve direct comparison of temporal and spatial variables (cf. Anderson, Lowit, & Howell, 2008).

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