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ORIGINAL ARTICLE

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Effects of delayed auditory feedback on timing of music performance

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Abstract Three experiments examined effects of delayed auditory feedback (DAF) on music performance as a function of the temporal location of feedback onsets within produced inter-onset intervals (IOIs). In Experiment 1, pianists performed isochronous melodies at two production rates with different amounts of DAF. Timing variability decreased for DAF amounts that caused feedback onsets to occur halfway through IOIs (binary subdivisions) in a 500-ms, but not 600-ms, IOI rate condition. In Experiment 2, pianists performed melodies with DAF delays and chose a preferred rate. Performers chose slower rates for larger delays; preferred rates approximated twice the amount of DAF. Experiment 3 tested the possibility that subjects deliberately conceptualized subdivisions in Experiments 1 and 2. Performers were given (1) no instructions, (2) instructions to mentally subdivide produced events in two, or (3) instructions to mentally subdivide produced events in three, in different blocks. Instructions to subdivide reduced timing variability for larger feedback delays. These experiments indicate that DAF disruption is reduced by subdividing instructions and sometimes by coincidences of feedback onsets with subdivisions of produced intervals. Such facilitation may reflect the use of hierarchical cognitive plans in production.

Introduction

Many studies have shown that altering the timing of auditory feedback substantially disrupts sequence production (see Finney, 1997, 1999; MacKay, 1987 for reviews), even though the absence of feedback does not (Repp, 1999). This paradigm, known as delayed auditory feedback (DAF), is implemented in music performance by inserting a lag between the time of produced onsets (e.g., a piano keypress) and the sounded (pitch) event onset. Studies of DAF document its disruption in a variety of tasks including music performance, speech, and tapping (e.g. Fairbanks, 1958; Finney, 1997; Gates, Bradshaw, & Nettleton, 1974; Howell, Powell, & Khan, 1983; Lee, 1950; MacKay, 1987; Robinson, 1972; and Finney & Warren, Delayed auditory feedback and rhythmic tapping: evidence for a critical interval shift, submitted). Measurements of disruption include changes in production rate (usually slowing) and serial ordering errors. Timing variability may also increase with DAF amount, although this possibility has not been pursued in past studies. Often, disruption increases with delays up to 200 ms and then diminishes (e.g., Gates et al., 1974; Howell et al., 1983; MacKay, 1987). Studies in which production rate is controlled with a pacing signal have found that the point of maximal disruption occurs at larger delays for slower rates (Robinson, 1972; and Finney & Warren, submitted). Some researchers have claimed that efforts to ignore DAF and practice with DAF alleviate its disruption (e.g. MacKay, 1987; but see Smith, 1962).

Many explanations have been offered for the robust effects of DAF in production tasks. One account is the "rhythmic displacement hypothesis" of Howell et al. (1983), which ties DAF disruption to desynchronization between produced actions and the perceptually displaced feedback signal, and predicts that DAF becomes more disruptive as delay amount increases up to the onset of the next produced event. Although this hypothesis implicates rhythmic relationships between produced actions and perceived events in the effects of DAF, it does not make strong claims about particular rhythmic phase relationships between DAF onsets and produced inter-onset intervals (IOIs). We postulate that certain asynchronous phase relationships between DAF and produced events may be less disruptive than others,

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in addition to the generally disruptive effect of feedback that is desynchronized from actions.

This prediction stems from research in motor control and perception. Research in motor control shows less variable interlimb coordination when the phase relationship between two moving limbs, sharing the same period, corresponds to a simple harmonic integer (Kelso, 1995; Yamanishi, Kawato, & Suzuki, 1980; Zanone & Kelso, 1997). Similarly, perception of moving patterns indicates that subjects can track fluctuations in the movements of two oscillating dots across a screen more accurately if the two movement patterns are coordinated in phase or antiphase (Bingham, Schmidt, & Zaal, 1999; Zaal, Bingham, & Schmidt, 2000). These findings are consistent with theoretical work that proposes a role of coordinative structures in perception, such as internal oscillators (Jones, 1976, Large & Jones, 1999). Support for the idea that such coordination patterns may cross modalities stems from a study in which subjects synchronized movements of a drumstick to an auditory metronome at various frequency ratios (Treffner & Turvey, 1993). Fewer shifts away from the prescribed frequency ratio were found for movements that were twice as fast as the metronome period (2:1), in which drumstick movements evenly subdivided metronome periods, in comparison with other frequency ratios that differed from the metronome period.

The experiments summarized in this paper address the question of whether performance under DAF benefits from certain asynchronous phase relationships between produced and perceived event onsets. Specifically, we tested the hypothesis that disruption from DAF is reduced when feedback onsets occur at temporal positions that evenly subdivide produced IOIs. If coordination patterns also apply to temporal relationships between produced actions and auditory feedback, disruption from DAF may be reduced when feedback onsets occur directly between produced onsets, forming binary subdivisions, as shown in Fig. 1a. When DAF onsets do not coincide with subdivisions of produced events, as shown in Fig. 1b, the interference between feedback timing and planned timing may result in higher variability in production (temporal disruption). We tested this prediction by measuring timing variability in piano performance under different tempo conditions in which DAF onsets fall at prescribed timepoints within produced IOIs (Experiments 1 and 3), and by allowing subjects to choose temporal relationships between IOIs and feedback by selecting a tempo for a given DAF amount (Experiment 2).

It is possible that a central mechanism controls coordination between IOIs and the temporal location of feedback onsets. Many researchers have proposed the existence of hierarchical mental plans underlying the timing of produced sequences such as speech and music (e.g., MacKay, 1987; Rosenbaum, Kenney, & Derr, 1983; Palmer, 1997; Todd, 1985; and Meyer & Palmer, Production rate and tactus effects in music performance, submitted). Subdivisions may constitute a microstructural time scale of such planning. For example, binary subdivisions are nested within produced IOIs in Fig. 1a and b, forming a two-level temporal hierarchy. Support for the use of mental subdivisions is seen in perceptual and memory tasks (Palmer & Krumhansl, 1990; Jones & Yee, 1997), and has a basis in music-theoretic depictions of temporal relationships (Lerdahl & Jackendoff, 1983). Furthermore, recent evidence has suggested that benefits found for antiphase coordination stem from the mental representation of time (Semjen & Ivry, 2001), which adds some support for the application of hierarchical plans to this microstructural level. Finally, musicians' ability to plan sequence events is correlated with measures of event timing in music performance (Drake & Palmer, 2000; Palmer & van de Sande, 1995). One ramification of the mental planning hypothesis is that disruption at delays that subdivide IOIs may be further

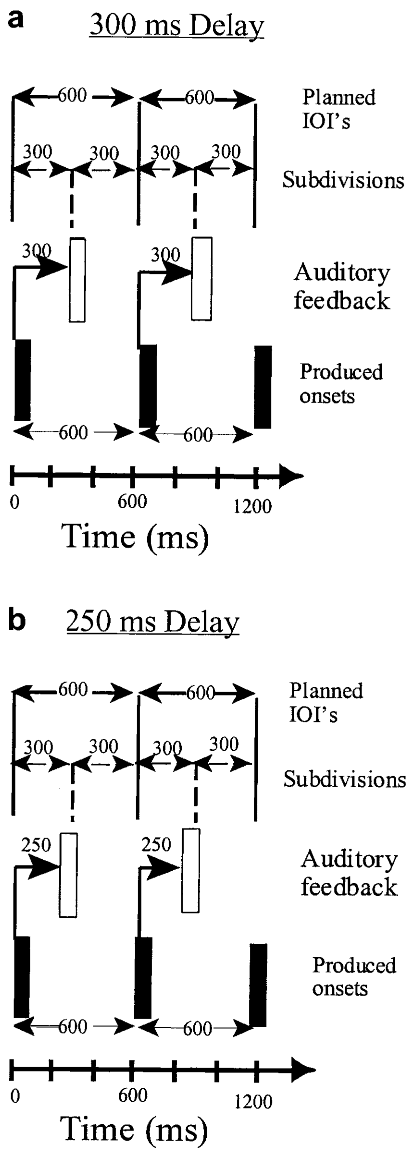

Fig. 1. Depiction of delayed auditory feedback conditions in a sequence produced at a 500-ms IOI (**a**) and 600-ms IOI (**b**), with binary subdivisions of produced IOIs (*IOI* = inter-onset interval)

reduced when performers deliberately attempt to subdivide. Furthermore, performers may be able to deliberately plan binary (shown in Fig. 1) or ternary (IOIs divided into three parts) subdivisions, both of which are common in music perception and composition (Lerdahl & Jackendoff, 1983; Palmer & Krumhansl, 1990). We tested these hypotheses in Experiment 3.

We explored these hypotheses about the temporal relationship between DAF and temporal variability of music performance in three experiments. Furthermore, we investigated disruption from DAF with a new measure: The temporal variability of produced IOIs, as measured by the coefficient of variation (standard deviation/mean IOI). This index allows timing variability to be examined independently of production rate (cf., Ivry & Hazeltine, 1995; Wing & Kristofferson, 1973). In Experiment 1, we tested the effect of different DAF delays on timing variability of musical sequences performed at two production rates (500- and 600-ms IOIs). Disruption should increase overall as delays get larger[1], but disruption should decrease when the delay is equal to a binary subdivision of the IOIs, relative to otherwise increasing disruption. In Experiment 2, we investigated whether subdivisions constitute preferred temporal relationships between DAF and produced IOIs, by measuring the effect of DAF on performers' preferred production rates. Performers should prefer rates that align feedback onsets with binary subdivisions of produced IOIs. In Experiment 3, we tested the degree to which subdividing stems from cognitive planning by instructing performers to mentally subdivide produced IOIs in twos or threes while performing musical sequences with DAF. Disruption should decrease with deliberate subdivisions, more so for delays equal to planned binary or ternary subdivisions of IOIs.

Experiment 1

Experiment 1 tested the hypothesis that DAF disruption would be reduced at delays whose onsets marked binary subdivisions. Subjects performed melodic sequences at two production rates (500- and 600-ms IOIs), with instructions to maintain a constant rate for each of seven auditory feedback delay conditions. Temporal disruption was measured in terms of timing variability (coefficient of variation, or SD/mean IOI) in each performance.

Methods

Subjects

Pianists from the Ohio State University music community participated in exchange for course credit in introductory psychology or nominal payment. The data from 11 subjects were discarded because of failure to maintain the prescribed tempo, based on the criterion of a mean IOI within 50 ms of the prescribed tempo on at least 70% of all trials[2] Nevertheless, the strict criterion of 50 ms was necessary given our goal of examining temporal relationships between DAF and produced IOIs. The remaining 19 subjects (18 of whom were right-handed) had an average of 12 years' private piano training (range 6–24 years).

Stimulus materials

Two short melodies, each notated in 4/4 meter, served as stimulus materials. One melody was in the key of C major, the other in F major. Each melody contained 8 isochronous quarter-note pitch events that formed the arpeggiated I and V^7 chords in the diatonic scale (e.g., stimulus 1 = C4 E4 G4 C5 D4 F4 G4 B4). Melodies were designed to be easy to produce and repeatable without changes in hand position. Stimuli were performed with the right hand only, and directions for fingering were indicated under the musical notation.

Apparatus

Melodies were performed on a Roland Juno-106 synthesizer with the preset sound patch 61 (with attack and decay characteristics similar to those of a piano). Subjects' view of the keyboard was obstructed by a sheet of cardboard approximately 32 centimeters above the keyboard, to reduce any effects of visual feedback on performance. The auditory output from the synthesizer was delayed using a Digitech S-200 digital delay, and was amplified with an EV BK-832 mixer. Subjects heard auditory feedback through AKG-K270 headphones at a comfortable listening level. Length of feedback delay was manipulated by MIDI control change commands from a personal computer. Performance tempo was established by a Seiko Quartz electronic metronome, sounded on a Labtech CS-550 portable speaker. Keypress responses were recorded by computer from the keyboard's MIDI output with 2-ms timing resolution.

Design and procedure

The experiment included seven delay amounts [0 (no delay), 100, 150, 200, 250, 300, and 350 ms], crossed with two tempo conditions: 600-ms IOIs (100 beats per min) and 500-ms IOIs (120 beats per min). These conditions formed the primary 7 (delay) × 2 (tempo) within-subjects design used in this experiment. Trials were blocked by tempo and subjects performed one of the two stimuli in each tempo block. The order of delays was randomized in each block, with the constraint that delay amount should not increase or decrease over more than two successive trials. The no-delay condition began each block. Counterbalance orders of tempi and stimulus item varied across subjects.

The procedure was a modified synchronization/continuation task. In each test trial, subjects performed four repetitions of one of the stimuli (32 IOIs) with normal feedback, in synchrony with the metronome. After this initial "synchronization" phase, there was brief pause during which the amount of delay was set (if applicable), and the metronome was turned off. Subjects then performed eight continuous repetitions of the same stimulus (64 IOIs) in the "continuation" phase. Subjects were instructed to maintain a legato (connected) articulation, and to avoid correcting any pitch errors.

[1]We do not expect that disruption will reach asymptote because the delays used here were shorter than those previously noted to yield maximal disruption by Finney & Warren (submitted), who used a similar synchronization-continuation task.

[2]The 50-ms criterion was used because it defines the midpoint between the two prescribed production rates. It was difficult for performers to maintain this level of accuracy in performance because of the common slowing effect of DAF on production rate (e.g. Gates et al., 1974).

At the beginning of a session, subjects practiced the stimulus for that block with normal auditory feedback, until it was memorized and performed with no errors. The music was then removed and view of the keyboard was obstructed. Then subjects performed the piece with a practice feedback delay (delay = 175 ms, a generally disruptive delay that was not used in the experiment) at a moderate self-paced tempo, eight times continuously. Following this familiarization with DAF, subjects performed one practice trial, using the 175-ms delay in the "continuation" phase. Practice trials were not included in data analyses. Subjects then performed a test trial for each of the 7 delay conditions at the first tempo. After a break, subjects practiced the second stimulus item with an unobstructed view of the keyboard, followed by test trials for each delay condition at the other tempo, during which their view was obstructed. The entire session lasted about 35 min.

Results and discussion

The coefficient of variation or CV (standard deviation of IOIs/mean IOI) was computed for each trial as the primary measure of timing variability. Eight-note cycles that contained pitch errors were removed from further analyses to avoid timing variability resulting from errors; the mean error rate per trial was less than 1% of note events and this removal resulted in a loss of 8% of total IOIs. The remaining IOIs (total $n = 64$ for trials without errors) in each trial were adjusted for tempo drift by adding the residuals from a regression of IOI on sequence position to the mean IOI. CVs were then computed on the adjusted IOIs for each trial. A one-way analysis of variance (ANOVA) on mean CVs by block (1, 2) yielded no main effect ($P > 0.1$), indicating that timing variability did not change over the session.

Mean CVs across delay conditions within each tempo condition are shown in Fig. 2. Comparisons of CVs in the no-delay conditions showed no differences across tempo, $t(18) = -0.18$, $P > 0.1$, suggesting that the baseline variability under normal feedback conditions was proportional to mean produced IOIs. Linear regressions fitted across the six delayed feedback conditions (excluding the no delay condition) within each tempo established increasing variability at larger delays. The fit to the regression line was significant for each tempo condition, $\beta = 0.0003$, $r = 0.93$, $P < 0.01$ for 500 ms, $\beta = 0.0001$, $r = 0.98$, $P < 0.01$ for 600 ms, and the difference between slopes was significant within individuals, $t(18) = 4.57$, $P < 0.01$ (two-tailed).

Next we tested whether the mean CV at each delay fell significantly below the regression line. We predicted that CVs for feedback delays that coincided with binary subdivisions of produced IOIs should fall significantly below the estimated regression lines (250 ms in the 500-ms tempo and 300 ms in the 600-ms tempo). The 500-ms tempo condition, shown in Fig. 2a, showed a significantly decreased CV relative to the predicted regression line at the 250-ms delay (one-tailed), $t(18) = 3.46$, $P < 0.01$. The mean CV at 250 ms was smaller than the mean of the two surrounding delays for 14 out of 19 subjects (binomial sign test, $P < 0.05$). No other delays fell significantly below the regression line. Results from the 600-ms tempo condition, shown in Fig. 2b, indicated

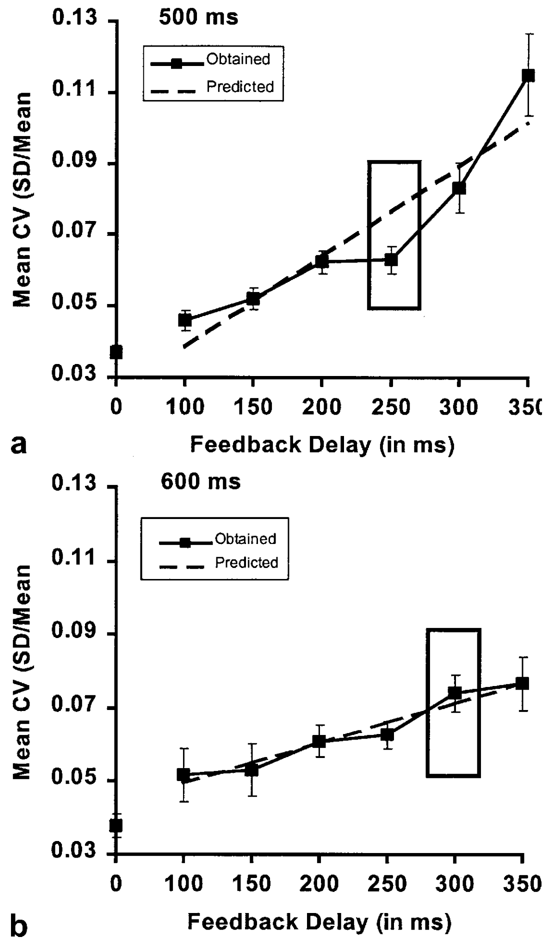

Fig. 2. Mean CV by delay condition for the 500-ms IOI condition (**a**) and 600-ms IOI (**b**) tempo conditions in Experiment 1. *Solid lines* indicate obtained CV measures, *dotted lines* indicate regression line. *Rectangles* highlight predicted and obtained CVs at delays corresponding to binary subdivisions. *Error bars* show between-subject standard errors (*CV* coefficient of variation)

that no CVs fell significantly below the regression line, either for individual or for mean data.

Experiment 1 confirmed that disruption from DAF results in more variable timing. The findings from the 500-ms tempo condition demonstrated reduced disruption when delayed feedback onsets coincided with binary subdivisions of IOIs. This suggests an underlying benefit for simple temporal relationships between produced timing and delayed feedback, an issue we explore further in Experiment 2.

Experiment 2

If performance timing under DAF benefits when feedback onsets coincide with binary subdivisions of IOIs, as suggested by the 500-ms IOI condition in Experiment 1, then performers may prefer tempi that are twice the amount of DAF. This prediction was tested in Experiment 2 with a task that required pianists to choose a tempo for different amounts of DAF.

Methods

Subjects

Sixteen subjects participated in this experiment after completing Experiment 1 (a subset of the participants in Experiment 1), in the same session. Subjects had 12 years' private piano lessons on average (range 6–24 years) and all professed to be right-handed.

Stimulus and apparatus

The same stimulus materials and apparatus were used as in Experiment 1.

Design and procedure

Experiment 2 contained one within-subjects variable, feedback delay, with four levels (200, 250, 300, and 350 ms), and the dependent variable was preferred tempo, measured by mean IOI. The four delay conditions were randomly ordered for each subject. Experiment 2 was run directly after subjects completed Experiment 1. Subjects were told that they should choose a tempo in a moderate range on each trial that seemed to "fit well" with that delay. The subjects chose either the F major or the C major stimulus melody for all trials to maximize ease of performance. The following procedure was then repeated for each of the delay conditions: subjects performed the melody while varying the tempo, until a comfortable tempo was chosen. Subjects indicated when a preferred tempo had been chosen, and they were instructed to perform at that tempo for eight stimulus cycles ($n = 64$ IOIs), which were recorded.

Results and discussion

Figure 3 shows the mean IOI for each trial in each delay condition, as well as predicted values (predicted IOI = 2× delay). The mean preferred IOIs were slower for increasingly larger delays, $F(1, 15) = 297.83$, MSE = 72,154.4, $P < 0.01$. The obtained mean IOI differed from the predicted IOI in only one of four delay conditions; the obtained IOI in the 200-ms delay condition was significantly larger than the predicted value, $t(15) = 5.04$, $P < 0.01$. We also examined the slope values from individual regressions of obtained IOIs on delay amounts; the predicted values yield a slope of $\beta = 2$. The obtained mean slope value ($\beta = 1.03$) differed significantly from the predicted slope, $t(16) = 5.55$, $P < 0.01$. Obtained data may also reflect a modulating effect of an absolute preferred tempo (e.g., Drake & Botte, 1993; Fraisse, 1982; Parncutt, 1994) which would predict a slope = 0. However, the obtained mean slope also differed significantly from zero, $t(15) = 5.349$, $P < 0.01$, indicating that DAF influenced tempo beyond any preferred tempo.

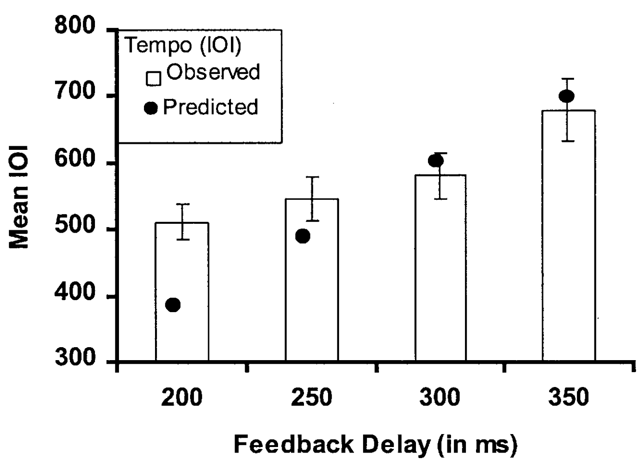

Fig. 3. Preferred tempo measures (mean IOI) by delay condition and predicted values of binary subdividing in Experiment 2. *Error bars* show between-subject standard errors

Experiment 2 provides some additional support that DAF disruption in music performance is reduced at binary subdivisions of produced IOIs, in that performers tended to prefer IOIs in which DAF onsets coincided with binary subdivisions. Two issues warrant further discussion. First, the significant difference between predicted and obtained IOIs at the 200-ms delay might reflect a discontinuity in time perception and production between slower and faster durations: Some research suggests that durations under 200 ms are governed by grouping, and are therefore not applicable to ratio-scale metrics such as Weber's law (Friburg & Sundberg, 1995; Hibi, 1993; Peters, 1989). It may therefore be difficult for pianists to incorporate such short durations as a binary subdivisions. Second, it was not clear whether subjects in Experiment 2 deliberately attempted to align feedback onsets at subdivisions of produced IOIs. The instructions may have encouraged subjects to vary their tempo from trial by trial or to conceptualize subdivisions within IOIs[3]. The fact that these subjects had just completed Experiment 1, in which tempo was varied, may also have encouraged variations in tempo. This second issue bears on the degree to which reduction of disruption reflects cognitive planning that includes subdividing, a question we pursued in Experiment 3.

Experiment 3

We suggested earlier that subdivisions of produced IOIs may constitute part of a hierarchical representation or plan used to guide sequence production. Experiment 3 addressed the role of deliberate planning by providing instructions to performers in one of three conditions: no instructions, instructions to subdivide IOIs into two intervals (subdivide-2), and instructions to subdivide IOIs into three intervals (subdivide-3). One possibility is that deliberate attempts to subdivide will further reduce disruption from DAF at delay amounts that match the planned subdivision. A further prediction is that musicians will be able to conceptualize binary or ternary subdivisions of produced IOIs that result in reduced disruption for certain DAF amounts. A second motivation for Experiment 3 was to discern why the predicted effect for Experiment 1 was not found for the

[3]It should be noted, however, that these instructions do not encourage subjects to position DAF at binary subdivisions.

600-ms IOI condition. Therefore, all trials in Experiment 3 were performed at a rate of 600-ms IOIs to test whether deliberate subdividing in two would yield the effect predicted for Experiment 1.

Experiment 3 included four delay conditions (none, 200 ms, 300 ms, 400 ms). The no-instruction condition was predicted to yield a linear increase in disruption over delays, as in Experiment 1. Instructions to subdivide in two were predicted to yield reduced disruption at the 300-ms delay (1/2 of 600-ms IOIs), and instructions to subdivide in three were predicted to yield reduced disruption at both 200- and 400-ms delays (1/3 and 2/3 of 600-ms IOIs, respectively).

Methods

Subjects

Pianists from the Ohio State University music community participated in exchange for course credit in introductory psychology or nominal payment. The data from 12 subjects were discarded because of an inability to maintain a mean IOI within 50 ms of the prescribed tempo on at least 75% of all trials. The remaining 12 subjects had an average of 11 years' private piano training (range 4–15 years). Ten subjects professed to be right-handed. One subject had also participated in Experiment 1.

Stimuli and apparatus

The same melodies were used as in the first two experiments. Subjects performed melodies on a Roland RD-600 weighted-key digital piano, which simulates the feel of an acoustic piano, with preset sound patch 11 whose timbre is similar to that of an acoustic grand piano. Performance tempo was established at the beginning of trials by a Boss DB-88 electronic metronome using a low-frequency click, heard over headphones through an EV BK-832 mixer.

Design and procedure

The experiment included four levels of delay (0, 200, 300, and 400 ms, corresponding to binary and ternary subdivisions of 600-ms IOIs) and three levels of instruction (no instructions, subdivide in two, subdivide in three), yielding a 4 × 3 within-subjects design. Subjects performed both stimulus items in each instruction condition. Trials were blocked by instruction condition and by stimulus (key of C or F) within instruction condition. The block of no-instructions trials always occurred first in a session, and the no-delay condition occurred first within each instruction-by-stimulus block. Counterbalancing order of the subdivide-2 and subdivide-3 instruction conditions and stimulus order varied across subjects.

Trials were conducted as in Experiment 1, except that all trials were performed at a rate of 100 quarter-notes per min (600-ms IOIs). Practice trials at the beginning of each session were conducted as in Experiment 1. Prior to the subdivide-2 and subdivide-3 instruction blocks, the experimenter gave instructions in which subdividing was described as "counting a rhythm in your head that is faster than the one you are playing, but that evenly divides the performed durations." An auditory demonstration of subdividing was then produced on the metronome. Subjects first heard the metronome at the rate of 600-ms IOIs; subjects were told that this was the performance tempo. A second click that indicated the subdividing rhythm was then sounded every 200 or 300 ms with the same timbre and frequency but at a lower volume, and subjects were told they should count at this rate silently while performing. Halfway through each instruction block, the subjects repeated all four delay conditions with the second stimulus, first practicing with an unobstructed view of the keyboard. The entire session lasted about 50 min.

Results and discussion

Pitch error removal and detrending for tempo drift were conducted on the IOIs for each trial as in Experiment 1. Pitch error rates were low (less than 1% of all sequence events, on average), and removal of measures surrounding errors resulted in the reduction of total IOIs by 5%.

Figure 4 shows the mean CVs for each instruction and delay condition. First, the CV measures were compared for no-delay trials across instruction conditions, for which no improvement is predicted from instructions. A one-way ANOVA confirmed no differences across the three blocks, indicating that experience with DAF in the session did not affect baseline variability. A 2-way ANOVA was then conducted on the CV measures for all delay and instruction conditions. There was a significant effect of delay on disruption, as found in Experiment 1, $F(3, 33) = 17.92$, MSE = 0.0007, $P < 0.01$, with lower disruption at the no-delay condition than at other delay conditions. There was also a significant effect of subdividing condition, $F(2, 22) = 3.4$, MSE = 0.0004, $P = 0.05$, with disruption being greatest for the no-instruction condition (mean CV = 0.0674). As shown in Fig. 4, instructions to subdivide reduced disruption most at the longer DAF delays; the interaction of instruction and delay approached significance, $F(6, 66) = 1.89$, MSE = 0.0003, $P < 0.1$.

CV values across delays within each instruction condition were examined for polynomial trends (linear, quadratic and cubic, adjusted for unequal intervals) to test whether timing disruption was reduced more when DAF onsets coincided with subdivisions. Only the linear

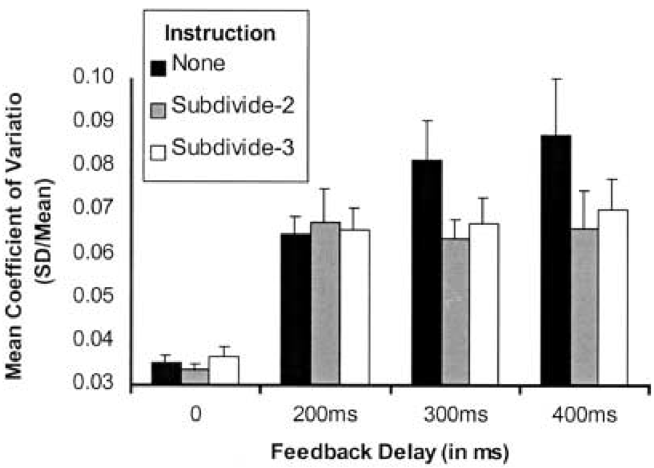

Fig. 4. Mean CV by delay condition and subdividing instruction condition in Experiment 3. *Error bars* show between-subject standard errors

component was significant for each instruction condition; the monotonic increase in disruption with delay was therefore not modulated by instruction.

In sum, Experiment 3 yielded two main findings. First, temporal variability increased with DAF, replicating the overall pattern of disruption across delays in Experiment 1. Second, deliberate subdividing reduced timing variability at longer feedback delays. Finally, Experiment 3 failed to demonstrate reduction of DAF disruption when feedback onsets coincided with planned subdivisions (300 ms for subdivide-2, 200 ms and 400 ms for subdivide-3), although there was a qualitative pattern of disruption for the subdivide-2 condition that fit predictions.

General discussion

Three experiments that investigated the effect of DAF on the timing of music performance yielded three main findings. First, patterns of timing variability (CVs) across delays converged with previous findings of disruption from DAF; temporal variability generally increased with amount of delay (Experiments 1 and 3). Second, disruption from DAF was reduced when feedback onsets occurred at subdivisions of produced IOIs, but only for the 500-ms performance tempo in Experiment 1. Experiment 2 offered converging support for this finding, as performers' preferred tempi coincided with twice the amount of delay on average for most conditions. Third, deliberate attempts to count subdivisions reduced DAF disruption for larger delays.

The beneficial effects of subdividing may reflect the incorporation of subdivisions in hierarchically structured plans for performance. We suggest furthermore that the disruptive effect of DAF may stem from difficulty performers have in maintaining temporal regularity in production when the temporal location of DAF onsets conflicts with planned timing. Feedback timing that more closely matches intended timing (such as feedback coinciding with binary subdivisions) may therefore result in less timing variability. This proposal is consistent with previous research that indicates musicians use feedback to monitor the accuracy of planned events, and that increased planning abilities coincide with increased temporal control in music performance (Palmer & Drake, 1997; Drake & Palmer, 2000).

The findings from the 500-ms condition of Experiment 1 and from Experiment 2 are consistent with other research that supports favored phase relationships in coordination based on principles of biomechanics (e.g., Treffner & Turvey, 1993). In addition, the demonstrated importance of temporal relationships between produced and perceived timing is consistent with the rhythmic displacement hypothesis' general rationale (Howell et al., 1983), although this hypothesis would not predict any effect of subdividing per se. The results of Experiment 3, however, disconfirm these alternative accounts: Subjects' deliberate attempts to count subdivisions during performance reduced timing variability under DAF – a result that cannot be accounted for by the rhythmic displacement hypothesis or by favored phase relationships without recourse to some higher-level mechanism, such as deliberate planning.

The procedure of Experiment 3 resembles the manipulation of counting instructions from research in time perception and production under normal feedback conditions (Hicks & Allan, 1979; Fetterman & Killeen, 1990; Getty, 1976; Grondin, Meilleur-Wells, & Lachance, 1999; Wearden, 1991). This work has revealed improved accuracy and decreased variability with counting, which has been used to support a clock-counter perspective of psychological time. In contrast, we find no differences across normal feedback conditions in Experiment 3, as predicted by clock-counter models that rely on Weber's law (Killeen & Weiss, 1987). Our obtained effects of counting instructions are limited to conditions with large amounts of DAF. The results from this experiment are therefore not fully accounted for by a clock-counter approach, although the finding of reduced disruption at longer delays is not inconsistent with such approaches.

An explanation of the disruptive effects of DAF based on a comparison between a mental plan for produced actions and auditory feedback is similar to control theory explanations of behavior (see Baron & Corker, 1989; Jagacinski, 1977; Wickens, 1992, for reviews), which have been used to account for DAF effects (Lee, 1950; Fairbanks, 1954). We do not propose a similar servo-mechanism account of disruption from DAF, given evidence that perceptual feedback is not necessary to guide production (Borden, 1979; Repp, 1999). Instead, we propose that a performer uses feedback, when available, to monitor whether the perceived signal's temporal location matches a planned timing hierarchy. Sequence production is therefore not dependent on the presence of auditory feedback, although this feedback is used when available. Furthermore, unlike control theory explanations, we do not claim that the disruptive effect of DAF is contingent upon performers' perception of feedback as related to their own actions. We predict that an external sequence (not related to performers' actions) with timing properties similar to those of DAF used here would have similarly disruptive effects, which is in agreement with the rhythmic displacement hypothesis (Howell et al., 1983).

The failure to find reduced disruption when DAF onsets coincide with subdivisions for 600-ms rate conditions remains a puzzle. The predicted "dip" at the 300-ms delay did not appear, even with the introduction of subdividing instructions in Experiment 2. One possibility is that the increased baseline variability of IOIs in the slower tempo condition (as shown in Fig. 2), combined with an absolute (non-proportional) amount of DAF, led to fewer occurrences of DAF onsets at binary subdivisions of produced IOIs for these conditions. Current research is addressing this possibility

(Pfordresher, 2001) by incorporating DAF in which delay amount adjusts proportionally with performance timing to maintain a consistent phase location relative to fluctuating IOIs (Finney, 2001).

In conclusion, disruption from DAF may result from an incongruity between produced timing and perceived timing that is mediated by mental plans that contain subdivisions of produced IOIs. On a more practical level, these results support the utility of deliberate subdividing in performance situations in which auditory feedback may be disruptive, such as a highly reverberatory room or in ensemble performance of music in which instruments are highly syncopated with one another. Heightened sensitivity to a lower hierarchical level in planning through subdividing may allow a performer to maintain stability under a greater range of rhythmically complex feedback.

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