EFFECTS OF ALTERED AUDITORY FEEDBACK ON THE TEMPORAL CONTROL OF DISCRETE AND CONTINUOUS MOVEMENTS

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ABSTRACT

Research indicates that distinct mechanisms regulate the timing of discrete and continuous rhythmic movements. These mechanisms – called event and emergent timing, respectively – may respond differently to auditory feedback. In this study, we investigated whether unexpected pitches in auditory feedback would interact with the timing accuracy of discrete and continuous rhythmic movements. Participants completed two tasks: finger tapping (Experiment 1) and circle drawing (Experiment 2). A synchronization-continuation paradigm was adopted whereby each action in the continuation phase triggered a sequence of repeated piano tones; however, in some trials, the auditory feedback of one tone of the sequence was altered. Our results indicate that unexpected feedback significantly affected timing accuracy of both discrete and continuous movements, but in unique ways. For the tapping task, the perturbations led to a decrease in the intertap interval immediately following the feedback manipulations. Conversely, in the circle-drawing task, unexpected pitch changes increased the inter-response interval on the second interval after the perturbation. These results indicate that unexpected changes in feedback content induced different error correction responses in discrete and continuous rhythmic movements, and shed light on adaptation and anticipation mechanisms in the temporal control of different types of rhythmic movements.

1. INTRODUCTION

Studies have recently demonstrated that distinct mechanisms control the timing of discrete and continuous rhythmic movements [1]–[4]. Discrete rhythmic movements are periodic actions preceded and followed by a period of little or no motion (e.g., finger tapping), and are thought to rely primarily on *event timing* mechanisms. On the other hand, the temporal regularity of continuous and smooth rhythmic movements (e.g., circle drawing) emerges from the control of movement dynamics, called *emergent timing* [1], [4]. Evidence suggests that event timing requires an explicit representation of a temporal interval to be produced based on an internal clock-like mechanism, whereas emergent timing arises from the dynamic control of nontemporal parameters of the movement, such as velocity, and therefore does not require an explicit internal representation of time [1], [3], [5]. The proposal that movements are based on distinct timing mechanisms has been supported by a series of studies demonstrating, for instance, that patients with cerebellar lesion exhibited increased variability for intermittent circle drawing (event timing) but not for continuous circle drawing [5]–[7]. Neuroimaging findings also suggest that event and emergent timing may recruit different brain areas [8], [9]. Finally, mathematical models of movement control are consistent with the possibility that the motor system relies on two different timing mechanisms [4].

Studies have shown that event and emergent timing mechanisms diverge in fundamental ways with respect to motor control, particularly in relation to the role of sensory feedback. For instance, Studenka and Zelaznik [10] first reported that continuous or cyclical movements do not exhibit auditory-motor synchronization due to the lack of perceptible events demarking each temporal cycle. However, further investigations demonstrated that the introduction of auditory [2], [11] or tactile feedback [12] at the end point of each cycle provided crucial temporal references required to generate an internal representation, thus enabling sensorimotor synchronization of continuous rhythmic movements.

To further investigate the role of auditory feedback in event and emergent timing, we examined the effect of unexpected perturbations of feedback content (i.e., pitch) on the timing of self-paced finger tapping and circle drawing. Experiment 1 focused on the effect of unexpected changes in feedback content on timed tapping, whereas Experiment 2 examined the effect of unexpected changes in feedback content on timed circle drawing. Based on the assumption that expected motor and perceptual outcomes are integrated into the motor commands [13], [14], these experiments tested whether feedback would be integrated into the representation of timing not only in event timing but also in emergent timing. It was predicted that feedback perturbations would significantly disrupt the timing of both event and emergent timing.

However, if this prediction were not confirmed, there would be reason to think that continuous and discrete movements are based on distinct timing and expectancy mechanisms.

2. EXPERIMENT 1: FINGER TAPPING

2.1. Method

2.1.1.Participants

Twenty-five undergraduate students (20 females) were recruited from the Department of Psychology at Macquarie University and received partial course credit for their participation. The average age was 20.1 years (*SD* = 6.4; range 18 to 44), and formal music training of participants varied from 0 to 13 years (*M* = 4.02; *SD* = 4.5). Only one participant reported being currently involved with musical activities for at least 2 hours weekly. None of the participants reported any form of hearing or motor impairment, and none had participated previously in a tapping experiment. This study was approved by Macquarie University Human Research Ethics Committee. All participants gave informed consent and were debriefed about the goals of the experiment after their testing.

2.1.2.Stimuli and Procedure

The experimental design followed the synchronization-continuation paradigm. Participants first synchronized eight taps with metronome tones presented at a fixed inter-onset interval of 600 ms. After eight taps the metronome stopped, and the participant attempted to continue tapping at the same pace, with each tap triggering a feedback tone. All feedback tones had a piano timbre. Participants were instructed to maintain the tempo set by the pacing signal to the best of their abilities until the end of the trial.

The feedback tones in the continuation phase were organized such that the first tone in every group of four tones was a piano tone of 392 Hz frequency (G4) and the other three tones were 261.63 Hz (C4), as depicted in Figure 1. This combination of feedback tones was repeated for 20 taps in the continuation phase (5 cycles). Similar patterns of feedback tones were presented in conditions 2 and 3 (i.e., a pitch change every fourth tone). However, in Condition 2 the expected pitch change (to G4) was unexpectedly displaced upward by one semitone (to G#4) at the 9th position of the continuation phase. In Condition 3, the expected pitch change (to G4) unexpectedly did not change (remained at C4) at the 9th position of the sequence. That is, the oddball was an *unexpected non-change*. In Condition 4, all feedback sounds were C4 piano tones, and there was only one unexpected pitch change (oddball) during the sequence of feedback tones (G#4). In Conditions 1-3, the cycle of four feedback tones implied a metric structure (repeated groupings of four tones), which was reinforced in Condition 4 by the introduction of a slight increase in intensity for the first tone within each group of four tones (+10 dB).

Figure 1. Representation of the auditory feedback sequence presented in the continuation phase for each of the 4 conditions.

Participants were given four practice trials (Condition 1) to familiarize themselves with the task and to ensure that they developed expectations for the feedback tones. Each condition was randomly presented 20 times, thus totaling 80 trials per participant. Trials were discarded and re-done immediately whenever any intertap interval (ITIs) was above or below 60% of the mean ITI for the trial. With breaks offered between blocks, the task took approximately 40 minutes to be completed.

2.1.3 Data Analysis

The synchronization phase ensured that the tempo was consistent across participants; thus, only the taps in the continuation phase were subjected to statistical analysis. To account for accelerations that can occur at the transition between synchronization and continuation phases the first five taps in the continuation phase were discarded, and the remaining 15 taps were subjected to analysis. ITIs were defined as the elapsed time between taps (in milliseconds). To evaluate general interference effects of oddballs on timing we analyzed participants' coefficient of variation (CV), which is defined as the standard deviation of ITIs within a trial divided by the mean ITI (SD/Mean). The average coefficient of variation was calculated across all trials for each condition.

The analysis focused on 3 ITIs before and 3 ITIs after the oddball presentation. Initial analysis indicated that there was no significant difference among the three intervals before the oddball. Therefore, for each trial, an average of 3 ITIs preceding the oddball was calculated and labeled as ITIp (where p = *pre-oddball*). The following ITIs were coded O, O+1, O+2 (where O = oddball). For the purpose of illustration, target ITIs were aligned and averaged across positions. ITI (ms) values were averaged across trials for each participant and each condition and subjected to a 4 x 4 repeated-measures ANOVA with two factors: Condition (4 levels) and Sequence Position (4 levels). Mauchly's test indicated that the assumption of sphericity had been violated for Sequence Position ($\chi^2(5) = 14.07$, $p = .01$, $\varepsilon = 0.70$). Therefore Greenhouse-Geisser corrections were applied to *p* values where appropriate.

2.2 Results

ITI (ms) values were analyzed, and results indicated a significant main effect of Sequence Position, F (3, 72) = 7.71, p = .001. Pairwise comparisons revealed that the sequence position immediately following the oddball tone was significantly shortened in comparison to all the other positions analyzed (O < P p < .001; O < O+1 p = .006; O < O+2 p = .02). There was a main effect of Condition, F (3, 72) = 11.47, p < .001. Across the taps that were analyzed, the mean ITI was larger in Condition 4 than in the other conditions. However, this main effect is qualified by a significant interaction between Sequence Position and Condition, which revealed that the effect of the oddball was quite different in the four conditions, F (9,216) = 11.77, p < .001. For Condition 1 (expected pitch change), there was no significant shift in the timing of taps (see Figure 2). This finding suggests that an *expected* pitch change does not affect the timing of motor actions. On the other hand, there was a significant effect of the oddball for all other conditions.

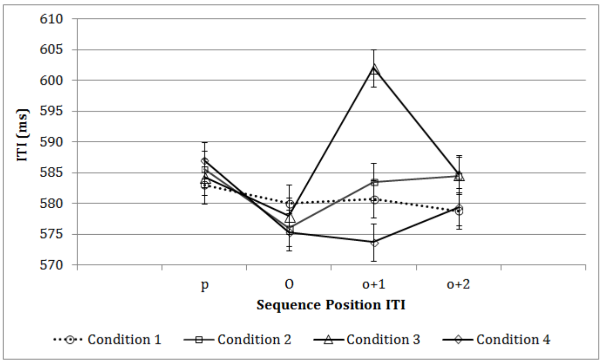

Figure 2. Intertap intervals (ms) displayed across conditions and sequence positions.

To further evaluate the effect of oddballs on timing we analyzed participants' coefficient of variation (CV). Each participant's CV values were averaged across trials for each condition and subjected to a repeated-measures analysis (ANOVA) with two factors (Condition, Sequence Position). There was a significant interaction between Condition and Sequence Position, F (3, 72) = 4.93, p = .004. Further analysis comparing the independent effect of each condition revealed that variability significantly increased after the oddball under Condition 3, suggesting that compensation was introduced after the perturbation (F = 11.001, p = .003). The coefficient of variation did not significantly change across trials in the other conditions. None of the other factors reached statistical significance.

2.3 Discussion

Experiment 1 tested the hypothesis that expectancy mechanisms mediate the interaction between feedback content and the timing of discrete motor actions, thus predicting that unexpected pitch changes in feedback would significantly interact with timing, while highly predictable pitch changes would not affect motor timing. Results confirmed this prediction by showing that only unexpected auditory feedback triggered by the discrete action significantly influenced the timing of tapping. Data revealed that unexpected feedback shortened the intertap interval immediately after the perturbation and induced a compensation in the following timing interval. The disruption of timing was observed in conditions where pitch changes were only 1-semitone, and also where an expected pitch change was omitted. These findings, therefore, suggest that expectations are intrinsic to timing and support the hypothesis that expected motor and perceptual outcomes are integrated into an internal representation [13], [14]. Further support to this finding was demonstrated by showing that expected pitch changes did not influence the timing of taps.

It was interesting to note that the effect of the unexpected pitch changes in the conditions tested affected the ITI trajectory in position o+1 significantly differently. Particularly, condition 3 - where an expected change was omitted - seems to have elicited a visibly higher overcompensation. This result suggests that expectancy mechanisms may process information on a continuous scale rather than as an all-or-none system. This suggestion is corroborated by a recent study that indicates that processing of expectancy violations is significantly modulated by the individual's action [15]. This research demonstrated that expectancy violations of one's action elicit brain responses that are significantly higher in amplitude than the passive perception of the same expectancy manipulations. In other words, expectancy violations evoke a much stronger neural response in the brain of the pianist than on the brain of the listener.

Experiment 1 supported the hypothesis of integration between feedback content and timing in event timing. However, it is not known whether unexpected changes in feedback content interact with emergent timing mechanism. This question was addressed in Experiment 2.

3. EXPERIMENT 2: CIRCLE DRAWING

3.1. Method

3.1.1.Participants

Twenty-four undergraduate students (13 females), average age 20 years (SD = 3.9 – range 18 to 36), were recruited from the Department of Psychology at Macquarie University and received partial course credit for their participation. Formal music training of participants ranged from 0 to 8 years (M = 2.45; SD = 2.5); however, only one participant was currently involved in music activities. None of the participants reported any form of hearing or motor impairment, and one had participated previously in a tapping experiment. All participants gave informed consent and were debriefed about the goals of the experiment after their testing.

3.1.2.Stimuli and Procedure

Experiment 2 was identical to Experiment 1, except for the task performed. In the circle-drawing task, participants repeatedly moved the computer mouse with the right index finger in a clockwise circular motion, tracing the circumference of a 5 cm diameter circular template displayed on the computer screen. Participants were instructed to synchronize their motion to the metronome so that the cursor would cross the mark positioned at 270 degrees on the circle at every click of the metronome.

Inter-response intervals were defined as the elapsed time between passes through the mark at 270 degrees. Participants were told that timing precision was more relevant than drawing accuracy, and they were free to choose the size of the circle they drew.

3.2. Results

To measure timing in the circle-drawing task, inter-response interval (IRI) was defined as the time elapsed between successive passes through the 270-degree mark. As in Experiment 1, in Experiment 2 IRI (ms) values were averaged across trials for each participant and each condition and subjected to a 4 x 4 repeated-measures ANOVA with two factors: Condition (4 levels) and Sequence Position (4 levels).

Results indicated a significant main effect of Sequence Position, F (3,69) = 5.79, p = .004, however pairwise comparisons revealed that unexpected pitch changes seemed to have interfered only in the position O+1 (O+1 > P, p = .005; O+1 = O p = .07; O+1 > O+2 p = .003). This result suggests that feedback changes did not interfere with the interval immediately after the oddball presentation as seen in the tapping task. It is also interesting to note that, unlike in event timing where unexpected changes tended to elicit a shortening of the interval immediately after the perturbation, in the circle drawing we see an *increase* in the interval after the perturbation.

More importantly, results indicated a main interaction of Condition and Sequence Position, F (9,207) = 2.69, p = .02, and post hoc tests revealed that Condition 1 (F (3,21) = 2.35, p = .10) and Condition 2 (F (3,21) = 2.87, p = .06) did not reach significance. Only Conditions 3 and 4 significantly interacted with intervals in the sequence position (F = 3.7 p = .02; F = 6.00 p = .004, respectively), as displayed in Figure 3.

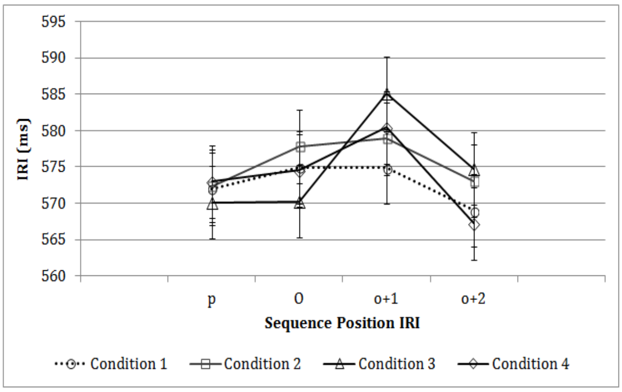

Figure 3. Inter-response intervals (ms) displayed across conditions and sequence positions.

Each participant's CV values were averaged across trials for each condition and subjected to repeated-measures ANOVA with two factors (Condition, Sequence Position). Results suggested that variability did not change significantly after the perturbation across conditions and sequence positions tested, as all factors did not reach significance (F <1). Comparing variability scores between performances on tapping (Experiment 1) and circle drawing (Experiment 2) showed that tapping was significantly more accurate than circle drawing, F (1,23) = 41.81, p < .001. Interestingly, correlation analysis indicated that variability in circle drawing and tapping tasks were not correlated (r^2 -0.32, n = 24, p = .11).

3.3. Discussion

Experiment 2 tested whether unexpected perturbations on feedback content would disrupt the timing of continuous movements, such as circle drawing. The assumption that expected motor and perceptual outcomes of one's actions are integrated into an internal representation, such as proposed by the forward models, would predict that feedback perturbations would significantly disrupt the timing of both event and emergent timing. Results confirmed the initial prediction by showing that timing of responses in the circle-drawing task was significantly affected by unexpected feedback changes. Interestingly, it was noted that not all conditions interfered with the timing of continuous movements, as conditions 1 and 2 did not disrupt timing intervals. In these conditions, a highly expected pitch change was introduced every four tones (condition 1) and a semitone change was introduced in one of these tones in condition 2. The fact that these conditions did not interfere with the timing in the circle-drawing task suggest that continuous movements are more resistant to interference. This suggestion is corroborated by the observation that unexpected perturbations of feedback content in conditions 3 and 4 interacted with timing, but only at position O+1 and O+2.

Our findings are consistent with recent studies showing that continuous movements have longer recovery times after a phase shift perturbation [16], which indicates that movements based on emergent timing have a "large inertia in that, once the limb is moving, it is very difficult to adjust this movement pattern" [12, p. 1098], [17].

4. GENERAL DISCUSSION

These experiments aimed to investigate the role of auditory feedback in event and emergent timing by testing whether perturbations of feedback content would significantly interact with the timing of self-paced discrete and continuous movements. Experiment 1 demonstrated the crucial role of expectancy in the interaction between feedback content and timing. Results showed that unexpected changes of nontemporal aspects of the feedback such as pitch significantly interacted with the timing of tapping. It was possible to observe that expected pitch changes occurring at predictable positions did not interact with the timing of intervals, which suggests that the results reported here are associated with violation of expectations rather than mere pitch change.

It was also shown that unexpected changes in feedback content interacted with the timing of continuous movements. This result adds support to the hypothesis that expectancy mechanisms are intrinsic to the timing of motor actions. However, the effect of unexpected changes in timing differed between tapping and circle drawing. For the tapping task, the oddball led to a *decrease* in the intertap interval at the interval immediately following the change in feedback tone. On the other hand, the oddball interacted with timing by *increasing* the inter-response interval on the second position (i.e., o+1) after the perturbation in the circle drawing.

These results are consistent with studies showing that continuous movements are slower than discrete movements in adjusting following changes in the sensory input [17], [16]. Repp [18] suggested that the difference in the interference effect of unexpected events in the two tasks is related to a greater "maintenance tendency" in continuous movements. This tendency is thought to be associated with the inertia associated with the movement [12], [17], [18].

Another interpretation of these results is the association of different expectancy processes. It has been recently suggested that emergent timing is based on "strong anticipation" processes [19]. According to this hypothesis based on dynamic system approach, strong anticipations arise from the close alignment between the action and its sensory outcome. In this case, the goal of the system is to maintain smooth and uninterrupted rhythmic movements based on global and often long-term expectations. Therefore, it is possible that the decoupling between motor actions and the external environment linked to strong expectations leads to a suppression of immediate interactions between unexpected events and the motor planning of self-paced movements. On the other hand, event timing seems to be associated with weak anticipation processes. This expectancy mechanism is required in dynamic environments where unpredicted events require rapid and efficient correction in order to maintain accurate responses. Therefore, it is thought that weak anticipations entail local and short-term expectancies [14], [19], [20]. It may be possible, therefore, that weak anticipations facilitate the intervention of error correction mechanisms in event timing resulting in immediate interactions between unexpected events and timing.

5. CONCLUSIONS

Results here described corroborate the notion that timing mechanisms (i.e., event and emergent timing) diverge in fundamental ways with respect to motor control and the role of auditory feedback. Here we show that unexpected nontemporal alterations in auditory feedback content (i.e., pitch) significantly interacted with the timing of self-paced discrete and continuous movements but in distinct ways. In the tapping task perturbations led to a *decrease* in the intertap interval at the interval immediately following the feedback manipulations. Conversely, in the circle-drawing task, unexpected pitch changes *increased* the inter-response interval on the second interval after the perturbation. These findings indicate that unexpected changes in feedback content induced different error correction response in discrete and continuous rhythmic movements. Further investigations are crucial to better understand the role of adaptation/anticipation mechanisms in the temporal control of different types of rhythmic movements.

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