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Attentional entrainment and perceived event duration

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This study considered the contribution of dynamic attending theory (DAT) and attentional entrainment to systematic distortions in perceived event duration. Three experiments were conducted using an auditory oddball paradigm, in which listeners judged the duration of a deviant (oddball) stimulus embedded within a series of identical (standard) stimuli. To test for a role of attentional entrainment in perceived oddball duration, oddballs were presented at either temporally expected (on time) or unexpectedly early or late time points relative to extrapolation of the context rhythm. Consistent with involvement of attentional entrainment in perceived duration, duration judgements about the oddball were least distorted when the oddball occurred on time with respect to the entrained rhythm, whereas durations of early and late oddballs were perceived to be shorter and longer, respectively. This pattern of results was independent of the absolute time interval preceding the oddball. Moreover, as expected, an irregularly timed sequence context weakened observed differences between oddballs with on-time and late onsets. Combined with other recent work on the role of temporal preparation in duration distortions, the present findings allot at least a portion of the oddball effect to increased attention to events that are more expected, rather than on their unexpected nature *per se*.

1. Introduction

Humans and other animals must accommodate many time scales of change in the environment, ranging from milliseconds-to-seconds to circadian and longer. Both the types and time scales of change experienced in day-to-day interactions with the environment pose unique challenges for understanding how brains work. Arguably, this is especially evident in audition because sound patterns are inherently extended in time and thus necessarily require the representation of temporal information and temporal patterns. In this regard, it is often the relative, rather than absolute, timing of information that matters for accurate perception. For example, in human speech, words can be spoken quickly or slowly and convey the same meaning. Similarly, in music, a melody can be performed at different tempi and retain its identity. How brains represent relative timing information and temporal structure in a manner that supports human perception and cognition is still very much a mystery.

The general question of interest here is how time and the temporal structure (e.g. the rhythm) of events in the environment guide attention in time. The overarching theoretical perspective guiding this research is that humans and other animals do not passively process temporal information, but rather are active perceivers, who are coupled with their environment. Thus, rhythms in the environment afford humans and other animals with the ability to predict the time course of future stimulation and guide the temporal allocation of attention. The roots of this perspective were put forward by Jones in 1976 [1], which later led to the development of dynamic attending theory (DAT) [2,3] and related attentional entrainment models [4–6]. The basic tenet of DAT and entrainment models is that endogenous attentional rhythms are synchronized by external (i.e. stimulus) rhythms, which then leads to the enhanced processing of events that occur at temporally expected time points.

Providing support for DAT and related entrainment models, a number of previous studies have revealed enhanced discrimination of events that occur at rhythmically expected time points compared with unexpected time points [3,5,7–9]. In this regard, there is further evidence that individuals have a preferred tempo (oscillation period) of processing information around approximately 500–600 ms and a limited tempo range of entrainment that varies systematically across the lifespan [6]. Recently, effects of rhythmic entrainment on the temporal allocation of attention have been shown to occur across modalities, with auditory entrainment influencing the allocation of visual attention [9]. DAT has also been applied to the domain of speech and language processing, providing evidence that attentional entrainment guides word segmentation and lexical access, enhancing phonological processing [10], spoken word perception for words that occur at rhythmically expected time points [11] and semantic sentence processing [12].

In this article, we extend previous research on DAT and entrainment models to investigate how attentional entrainment influences perceived event duration, rather than discrimination. Most past investigations of perceived event duration have considered a number of different factors that produce systematic distortions in an individual's temporal experience, including the amount of attention allocated to an event (see [13,14] for reviews). Many of these previous studies have typically taken the view that attention is allocated in a manner that is either for the most part uniformly distributed in time, or sustained at a constant level before declining, much like the brightness of a flashlight running out of battery power.

Generally, studies that have taken this approach have been framed using internal clock models, supporting the hypothesis that the more attention that is devoted to the temporal characteristics of an event, the longer the perceived duration [13–16]. Internal clock models propose that individuals time the duration of events using a mechanism that is essentially akin to a stopwatch [17–19]. A fundamental assumption is that individuals have control of some form of internal clock that can be arbitrarily started and stopped and, further, that independent representations of durations of timed intervals are stored in memory in a context-independent manner. Internal clock models, such as scalar expectancy theory (SET) [7,8], consist of three processing stages: clock, memory and decision [16,18]. Central to the effects of attention on perceived duration is the clock stage, which consists of pacemaker, switch and accumulator components. The pacemaker generates a continuous series of pulses. In response to a to-be-timed stimulus, a switch is closed, allowing pulses to flow into an accumulator that collects the pulses.

Within this framework, the number of accumulated pulses provides a representation of the duration of the stimulus. Attention has been proposed to affect this duration representation by altering the rate of the pacemaker or by altering the latency or efficiency of the switch. Both a faster pacemaker and more efficient switch enable greater pulse accumulation and are predicted to result in longer temporal estimates. Thus, from this perspective, shorter verbal estimates of time and also longer reproductions of target durations are predicted to occur in dual-task (divided attention) conditions compared with single-task (focused attention) conditions because dual-task conditions reduce attention to time and afford less pulse accumulation [14–16]. Effects of dual-task conditions on duration estimates consistent with this hypothesis have been reported using a wide variety of methods and a range of concurrent non-temporal tasks, including card sorting, mental rotation, visual search and anagram solving [14,20–23].

In the present investigation, we are interested in testing the predictions of DAT and attentional entrainment on the perception of the duration of an event. The key distinction between DAT and internal clock approaches to perceived event duration is that internal clock models, such as SET, assume that the internal clock is arbitrarily reset in response to each to-be-timed interval. That is, durations of successive events are timed independently in a context-independent manner. By contrast, DAT predicts that sequence rate (context) should influence the perceived duration of embedded stimuli because internal attentional oscillations are entrained by the rhythm of the context sequence; the perceived duration of an event is thus influenced by the phase of its onset relative to the expected time points based on an extrapolation of the context rhythm. The approach we have taken in this study to test DAT and effects of attentional entrainment on perceived event duration is to use a well-established oddball paradigm, in which individuals are typically asked to judge the duration of a deviant (oddball) stimulus embedded within a rhythmic sequence of otherwise identical stimuli.

Previous studies have shown that the duration of the oddball stimulus tends to be overestimated [13,24], but various factors influence the magnitude of this effect [25–27] and not all studies have revealed overestimation [28–30]. Tse and co-workers manipulated perceptual features of oddball/standards and standard duration (ranging from 75 to 2100 ms) in a series of experiments involving an oddball paradigm in which stimuli mostly consisted of simple visual shapes, but also included auditory oddball conditions [13]. Across conditions, Tse and co-workers found that the duration of the oddball was substantially overestimated; the degree of oddball overestimation ranged from as little as approximately 25% for auditory oddballs to as much as nearly 60% for visual oddballs. The amount of overestimation was proposed to be influenced by saliency of the oddball stimulus, where oddball salience was operationalized roughly as the amount of perceived change per unit of objective time. Consistent with this hypothesis, they found that when the oddball was a visually expanding disc it showed more temporal expansion (i.e. greater overestimation) than when the oddball was a stationary disc. To explain duration distortions observed for oddball stimuli, Tse and co-workers proposed that the unexpected oddball stimulus captures attention and increases the effective rate of accumulation of temporal information [13]. This view of the oddball effect leverages the internal clock model of timing, whereby the duration of the oddball is subjectively expanded relative to the standard because more attention to the oddball speeds the rate of the pacemaker and thereby increases the number of pulses accumulated over its temporal extent.

When considering perceived event duration, DAT and the attentional entrainment view contrasts quite starkly with internal clock models, which assume that the clock can be started and stopped equally well at all time points and that successive durations are timed independently; thus, from the perspective of SET, the temporal structure of a sequence of events does not affect the perceived duration of individual events. By contrast, one natural question that arises from an entrainment perspective is what role does the temporal structure (i.e. rhythm) of the sequence play in generating systematic distortions in perceived duration? Note that when the standard sequence is isochronous, the timing of the onset of the oddball stimulus occurs on time with respect to the rhythm established by the sequence of standard tones. In

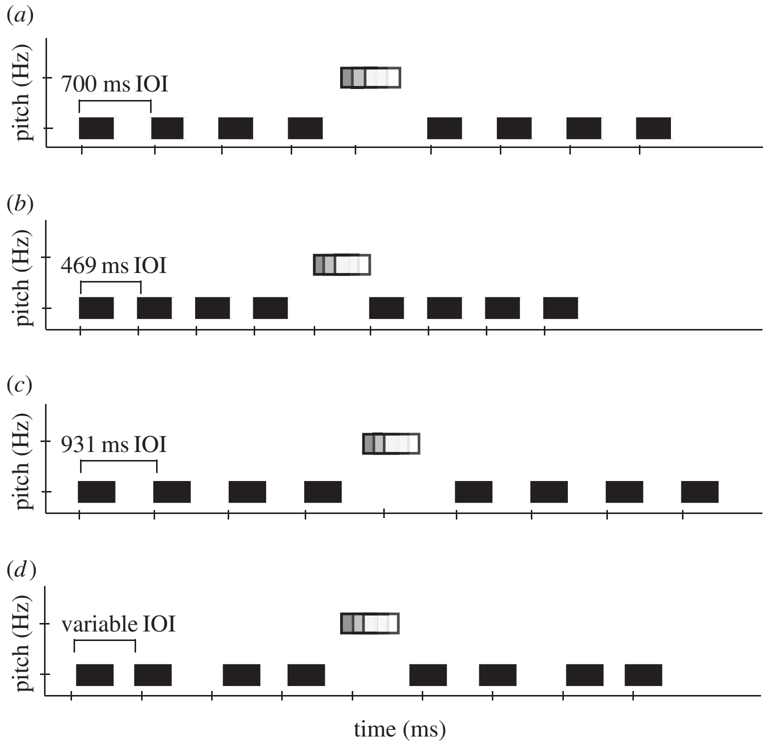

Figure 1. Diagram illustrating a single trial in the auditory oddball paradigm. On each trial, participants heard a sequence of nine tones that included eight standards (black rectangles) and one embedded oddball tone identified by a different pitch that occurred in the 5th, 6th, 7th or 8th position. Oddball tones were presented at one of three intervals after the preceding standard, these were: 469 ms (dark grey rectangle), 700 ms (light grey rectangle) and 931 ms (white rectangle). In Experiment 1, standard tones were presented isochronously with an inter-onset-interval (IOI) of 700 ms (*a*); thus, in this condition oddball onsets corresponded to relatively early, on-time or late presentations. In Experiment 2, standard tones were presented isochronously with an IOI of 469 ms (fast tempo, *b*) or an IOI of 931 ms (slow tempo, *c*). In the fast tempo condition, oddball onsets corresponded to relatively on-time, late or very late presentations; conversely in the slow tempo condition, oddball onsets corresponded to very early, early or on-time presentations. Finally, in Experiment 3, tones were presented with a variable IOI (irregular timing, *d*).

terms of DAT, this means that the oddball occurs at a peak in attentional energy. Of interest then is the question of what happens when the oddball occurs at unexpected time points that are early or late with respect to the rhythmic context.

To address this question, we conducted a series of three experiments in which we manipulated the timing of the onset of the oddball relative to the preceding rhythm of standard stimuli (figure 1). In all experiments, listeners judged the duration of the oddball stimulus relative to the duration of the standard stimulus. Experiments 1 and 2 used isochronous standard rhythms that tested different tempo conditions for the standard rhythm, but maintained the same set of absolute intervals preceding the onset of the oddball. Oddballs were presented 'on time' (at the expected time point based on an extrapolation of the standard rhythm), or they occurred 'early' (before the expected time point) or 'late' (after the expected time point). By using different tempo conditions for the standard rhythm in the first two experiments, we were able to separate the effect of the relative timing of the oddball onset (early, on time and late) from any effect of the absolute interval preceding the oddball onset.

Because early oddballs occur before they are temporally expected based on the entrained attentional rhythm, DAT predicts that they should receive less attention and be perceived to be shorter compared with on-time oddballs. With respect to late oddballs, there are two possibilities to consider. First, because late oddballs, like early oddballs, are temporally unexpected (i.e. off the peak of the attentional rhythm), a strict interpretation of DAT would suggests that late oddballs would also receive less attention and be perceived to be shorter in duration relative to on-time oddballs. However, late oddballs are temporally unexpected in a slightly different way because of the direction of time's arrow. Early oddballs occur before listeners have generated the expectation for an event based on the entrained rhythm, whereas late oddballs occur after listeners have generated the expectation for an event. Thus, because participants are expecting an oddball to occur on each trial, the absence of an event at the expected time point serves as a potential cue for participants to expect the oddball to occur at a later time point. From this alternative perspective, late oddballs should receive heightened attention and be perceived to be longer in duration than on-time oddballs. In the final (third) experiment, we introduced variability in the timing of the standard rhythm, but still maintained the same set of absolute intervals preceding the onset of the oddball. Here, DAT predicts that an effect of attentional entrainment should be weakened (or possibly even eliminated).

In sum, increased attention in both SET and DAT leads to longer perceived durations; it is the mechanism of attention and how duration is recorded that differs. In SET and the view of Tse *et al.* [13], attentional capture by perceptual salient oddball events leads to those being allocated relatively more attention that the less salient standard events. In DAT, attention is entrained by the temporal structure of event sequences, peaking at temporally predictable moments. By virtue of the one-directional nature of time's arrow, there is an inherent asymmetry between early and late events. Early events occur before the expected time point and associated attentional peak, and thus unequivocally should receive less attention and be perceived to be shorter in duration than on-time events. Late events, by contrast, occur after the expected time point, and potentially receive heightened attention, because the absence of an event at the expected time point cues individuals to the pending occurrence of the oddball.

2. Experiment 1

(a) Material and methods

(i) Participants and design

Twenty-two undergraduate students (15 female, 18–22 years, $M = 19.9$, s.d. $= 1.4$) from Michigan State University, with self-reported normal hearing and varied levels of formal music training ($M = 3.7$ years, s.d. $= 4.2$ years) participated in the experiment in return for partial course credit. One additional individual completed the experiment but was not included in the final sample because of self-reported inattention to the task. The experiment implemented a 3 (oddball onset: early, on time, late) $\times$ 4 (oddball position: 5th, 6th, 7th, 8th) $\times$ 9 (oddball duration: -20, -15, -10, -5, 0, $+5$, $+10$, $+15$, $+20$%) within-subject design.

(ii) Stimuli and apparatus

The standard stimulus was a 350 ms 440 Hz sine tone and the oddball stimulus was an 880 Hz sine tone that varied in duration (350 ms $\pm$ 0, 5, 10, 15 or 25%); sampling rate for both stimuli types was 44.1 kHz. The inter-onset-interval (IOI) between successive standards was always 700 ms. The IOI preceding the oddball varied from trial to trial and was equal to 469, 700 or 931 ms corresponding to early, on-time and late onset of the oddball relative to the isochronous rhythm established by the standard. The IOI following the oddball was always 700 ms. Stimuli were generated using MATLAB software (The Mathworks, Inc.) and were presented at a comfortable listening level over Sennheiser HD-280 Pro headphones (Old Lyme, CT). Stimulus presentation and response collection using a serial button response box was controlled by E-PRIME v. 2.0 software (Psychology Software Tools, Inc.) running on a Dell Optiplex 760 series computer with Creative Sound Blaster Audigy soundcards.

(iii) Procedure

On each trial, participants heard a sequence of nine tones that consisted of eight standards and an embedded oddball (figure 1*a*). Participants judged whether the variable-duration oddball was *shorter* or *longer* in duration than the fixed-duration standard by pressing one of two labelled buttons on a response box. Experimental blocks were preceded by a 12-trial practice block. Each experimental block consisted of 108 trials. Oddball onset (469 ms—early, 700 ms—on time, 931 ms—late), position (5th, 6th, 7th and 8th) and duration (350 ms $\pm$ 0, 5, 10, 15, 20%) varied randomly from trial to trial. Within each 108 trial block, there was one observation for each combination of onset, position and duration. Each participant completed three experimental blocks, for a total of 324 trials (12 observations for each combination of onset and duration). Participants took short breaks between each block, and at the end of the third block they completed a survey that included questions about demographic background, music training and any strategies used. The entire experiment took approximately 90 min.

(b) Data analysis

Proportions of *longer* responses were determined for each of the nine oddball durations in each oddball onset condition. Resulting psychometric curves were used to derive estimates of the point of subject equality (PSE) and just-notable difference (JND) using the *z*-transform method prescribed by Macmillan & Creelman [31]. In constructing the psychometric curves, data were combined over the four oddball positions so that there were enough observations in each duration condition to obtain reliable estimates of PSE and JND. PSE measures the duration for which a participant responds *shorter* and *longer* responses 50% of the time (i.e. they perceive the oddball to be the same duration as the standard), whereas the JND is a discrimination threshold measure that reflects the slope of the psychometric curve (smaller JNDs correspond to steeper curves and better discrimination). JND is independent of PSE; it is measured by subtracting the estimated durations corresponding to the 75th and 25th percentiles on the curve and dividing by two (this is equivalent to determining the semi-inter-quartile range). We have expressed JNDs in relative terms as a percentage of the standard duration. This is calculated by dividing the obtained JND estimate by the standard duration and multiplying by 100. PSE estimates were used to calculate a duration distortion factor (DDF) by calculating the ratio of the point of objective equality (POE, i.e. the actual duration of the standard, 350 ms) to the PSE. A DDF greater than 1 indicates overestimation of the oddball duration, whereas DDF less than 1 indicates underestimation of the oddball duration. A DDF of 1 occurs when the PSE is equal to the POE (i.e. there is no systematic distortion in the perceived duration of the oddball).

The dependent measures for the statistical analyses were DDF (a measure of relative perceived duration) and JND. Repeated-measures ANOVAs on DDFs and JNDs with a single within-subject factor of oddball onset with three levels (early, on time and late) were used to assess whether there were reliable effects. Paired-samples *t*-tests assessing differences in DDFs between early versus on-time and on-time versus late conditions were used to provide a more detailed test of the predictions of DAT.

(c) Results and discussion

Figure 2 shows mean DDF as a function of relatively early, on-time and late onset oddballs. The repeated-measures ANOVA on DDFs revealed a main effect of oddball onset, $F_{2,42} = 7.28$, $p = 0.002$, $\eta_p^2 = 0.26$. In line with the predictions of DAT and the entrainment account, early oddballs were perceived to be reliably shorter ($M = 0.94$, s.d. $= 0.08$) than on-time oddballs ($M = 1.01$, s.d. $= 0.08$), $t_{21} = -2.40$, $p = 0.03$, $d = 0.51$. Conversely, late oddballs were perceived to be reliably longer ($M = 1.05$, s.d. $= 0.12$) than on-time oddballs, $t_{21} = 2.18$, $p = 0.04$, $d = 0.47$. Table 1 shows average discrimination thresholds (relative JNDs) as a function of early, on-time and late onset oddballs. Mean relative JNDs did not differ as a function of oddball onset, $F_{2,42} = 0.06$, $p = 0.95$, $\eta_p^2 = 0.003$.

Results from Experiment 1 are consistent with DAT and suggest that attentional entrainment influences perceived event duration in an oddball paradigm. As expected, relatively early oddballs, predicted to receive *reduced* attention because they occur before the peak of the entrained attentional rhythm, were perceived to be shorter in duration

Table 1. Relative JNDs for the three oddball onset conditions in isochronous sequences in Experiment 1 (moderate tempo), Experiment 2 (fast tempo), Experiment 2 (slow tempo) and the irregularly timed sequences in Experiment 3. Standard deviations are shown in parentheses.

	relative JNDs (%)			
onset condition (ms)	**Experiment 1**	**Experiment 2 (fast tempo)**	**Experiment 2 (slow tempo)**	**Experiment 3**
469	12.3 (5.0)	15.9 (12.1)	9.5 (2.4)	12.7 (5.2)
700	12.0 (5.5)	12.6 (6.6)	9.0 (2.7)	13.1 (6.9)
931	12.1 (4.7)	14.4 (7.0)	9.0 (3.4)	11.6 (2.9)

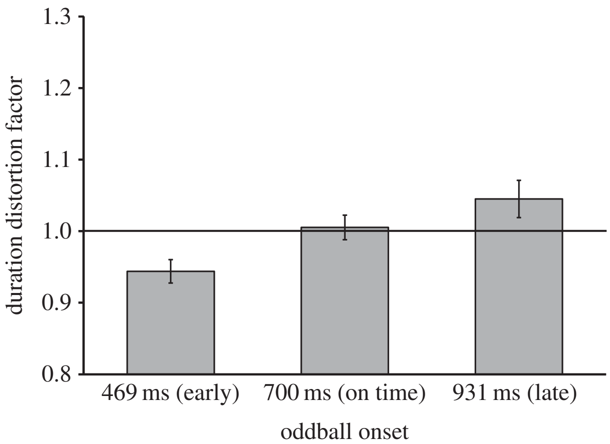

Figure 2. Mean DDF (with standard error bars) for oddballs presented with onsets of 469, 700 and 931 ms for the moderate standard tempo in Experiment 1.

than on-time oddballs. On-time oddballs that occurred at the expected time point based on the entrained rhythm showed little to no distortion in perceived duration. Relatively late oddballs, in contrast, were perceived to be longer in duration than on-time oddballs. Lengthening of perceived durations for late oddballs is consistent with DAT, as late oddballs occur after listeners have generated an expectation for an event to occur and the absence of an event at the expected time point serves as a cue that enhances attention to events. Relative onset timing did not appear to affect discrimination thresholds (i.e. JNDs).

One question that emerges from Experiment 1 is whether the observed effect is due to an effect of entrainment or may simply be due to having a short, medium or long interval preceding the oddball. That is, the longer the interval preceding the oddball, the more participants were able to predict that the oddball was going to occur (i.e. prepare for the oddball to occur), akin to a variable foreperiod effect [28–30]. To consider this possibility, we conducted a second experiment wherein we kept the short (469 ms), medium (700 ms) and long (931 ms) IOIs preceding the oddball the same, comprising the early, on-time and late conditions in Experiment 1, but varied the tempo of the stimulus sequence so that the *relative* onset time of the oddball varied. In particular, we either shortened the fixed IOI between standards (i.e. sped up the sequence) so that the short-interval onset was on-time, and the medium- and long-interval onsets were late and very late, or we lengthened the fixed IOI between standards (i.e. slowed down the sequence) so that the long-interval onset was on-time and the short- and medium-interval onsets were very early and early.

If the results of the first experiment are simply an effect of temporal preparation based on the absolute duration of the interval preceding the oddball, then the results for the short-, medium- and long-interval onsets in Experiment 2 should be the same as Experiment 1 for both tempo conditions. However, if the duration distortions observed in Experiment 1 reflect entrainment to the standard rhythm, then for the fast tempo condition where we shortened the fixed IOI between standards, the short-interval onset should now be on time and should show little-to-no duration distortion, whereas the medium- and long-interval onsets should be increasingly overestimated as these conditions are now late and very late with respect to the entrained rhythm. The parallel prediction should hold in the slow tempo condition where we lengthened the fixed IOI between standards: in this case, the long-interval onset is now on time and should thus show little-to-no duration distortion, whereas the short- and medium-interval onsets should be increasingly underestimated as these are now very early and early relative to the entrained rhythm.

3. Experiment 2

(a) Material and methods

(i) Participants and design

Forty-four undergraduate students (27 female, 18–22 years, $M = 19.2$, s.d. $= 1.0$) from Michigan State University with self-reported normal hearing participated in the experiment in return for partial course credit. Participants varied in number of years formal music training ($M = 2.8$ years, s.d. $= 4.2$ years). An additional eight individuals completed the experiment, but were not included in the final sample due to inattention to task, non-compliance with task instructions or exceptionally poor performance (relative JNDs $> 75\%$). The design of the experiment was a 2 (sequence tempo: fast, slow) $\times$ 3 (oddball onset: 469, 700, 931 ms) $\times$ 4 (oddball position: 5th, 6th, 7th, 8th) $\times$ 9 (oddball duration: 350 ms $\pm$ 0, 5, 10, 15, 20%) mixed-factorial design. Tempo was a between-subjects factor, whereas oddball onset, position and duration were within-subject factors. Participants were randomly assigned to either the fast tempo condition ($n = 20$) or the slow tempo condition ($n = 24$).

(ii) Stimuli, equipment and procedure

Stimuli, equipment and procedure were the same as Experiment 1, except for the tempo manipulation. The fixed IOI between successive standards was 469 ms in the fast tempo condition and 931 ms in the slow tempo condition (see figure 1*b* and *c*, respectively).

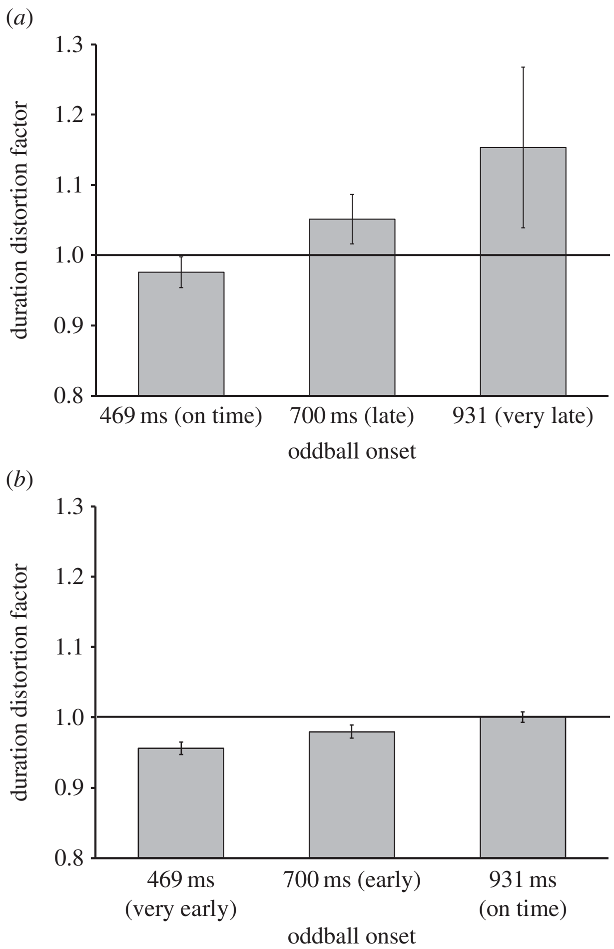

Figure 3. Mean DDF (with standard error bars) for oddballs presented with onsets of 469, 700 and 931 ms for the fast standard tempo (*a*) and the slow standard tempo (*b*) in Experiment 2.

(b) Results and discussion

Figure 3*a*,*b* shows the mean DDF as a function of oddball onset for the fast and slow tempo conditions. A 2 (sequence tempo) × 3 (oddball onset) mixed-measures ANOVA on DDFs revealed a marginal main effect of sequence tempo, $F_{1,42} = 3.44$, $p = 0.08$, $\eta_p^2 = 0.08$, a main effect of oddball onset, $F_{2,84} = 3.66$, $p = 0.03$, $\eta_p^2 = 0.08$, but no interaction between sequence tempo and oddball onset, $F_{2,84} = 1.33$, $p = 0.27$, $\eta_p^2 = 0.03$. Thus, for both tempi, the ANOVA reveals a similar pattern of change in DDFs as a function of oddball onset, but the distortions are mediated by tempo in the manner predicted by DAT and the entrained attention account. Note that in the fast tempo condition, the 469 ms interval served as the on-time condition and as predicted, there was the least distortion in perceived oddball duration in this condition (469 ms interval: $M = 0.98$, s.d. = 0.10). As oddballs occurred increasingly late in the 700 and 931 ms conditions, they tended to be perceived as increasingly longer (700 ms: $M = 1.05$, s.d. = 0.15; 931 ms; $M = 1.15$, s.d. = 0.51). Paired-samples *t*-tests, however, revealed only a marginally reliable difference between the 469 and 700 ms conditions, $t_{19} = 1.87$, $p = 0.08$, $d = 0.42$, and no reliable difference between the 700 and 931 ms conditions, $t_{19} = 1.17$, $p = 0.26$, $d = 0.26$. In the slow tempo condition, by contrast, the 931 ms interval served as the on-time condition and there was the least distortion in perceived oddball duration (indeed no distortion) in this condition ($M = 1.00$, s.d. = 0.04). As oddballs occurred increasingly early in the 700 and 469 ms conditions, they were perceived to be increasingly shorter (700 ms: $M = 0.98$, s.d. = 0.05; 469 ms: $M = 0.96$, s.d. = 0.05). Paired-samples *t*-tests revealed a reliable difference between the 931 and 700 ms conditions, $t_{23} = -3.17$, $p = 0.004$, $d = 0.65$, and between the 700 and 469 ms conditions, $t_{23} = 3.93$, $p = 0.001$, $d = 0.80$.

Table 1 shows average discrimination thresholds (relative JNDs) as a function of oddball onset for both tempi. With respect to discrimination thresholds, a 2 (sequence tempo) × 3 (oddball onset) mixed-measures ANOVA on JNDs revealed a main effect of sequence tempo, $F_{1,42} = 9.68$, $p = 0.003$, $\eta_p^2 = 0.19$, but no main effect of oddball onset, $F_{2,84} = 2.31$, $p = 0.11$, $\eta_p^2 = 0.05$, nor a reliable interaction between sequence tempo and oddball onset, $F_{2,84} = 1.31$, $p = 0.27$, $\eta_p^2 = 0.03$. Overall, discrimination thresholds were worse at the fast tempo ($M = 14.3\%$, s.d. = 7.6%) than at the slow tempo ($M = 9.2\%$, s.d. = 2.5%).

A final analysis combined the data from Experiments 1 and 2 and considered only duration distortions for the 700 ms oddball onset condition as a function of the three tempi. This analysis allowed us to consider the case where the absolute duration of the interval preceding the oddball onset was held constant, but the relative timing of the oddball onset was early, on time or late, depending on rhythmic context (i.e. the tempo of the isochronous standard sequence). Consistent with DAT and an entrainment account, a trend analysis revealed a reliable linear trend as function of relative oddball onset, $F_{1,64} = 5.8$, $p = 0.02$. Perceived durations were shortest in the early condition ($M = 0.94$, s.d. = 0.05), showed no distortion in the on-time condition ($M = 1.0$, s.d. = 0.08) and were longest in the late condition ($M = 1.05$, s.d. = 0.16).

In sum, results from Experiment 2 support DAT and an entrained attention account of observed duration distortions, over a simple temporal preparation account based on the absolute duration of the interval preceding the oddball onset. Independent of the absolute duration of the interval preceding oddball onset, oddballs that occurred early and late relative to the entrained rhythm were perceived to be shorter and longer in duration, respectively, compared with oddballs that occurred on time. Overall, the fast tempo condition appeared to be harder than the slow tempo condition, yielding higher discrimination thresholds and greater variability between subjects in both duration distortions and discrimination thresholds. Although the results from the first two experiments are consistent with DAT and the associated entrainment account, it is still not clear to what extent the isochronous nature of the sequences are responsible for the observed systematic pattern of distortions in perceived duration associated with onset timing. To address this issue, we conducted a third experiment where we varied the IOI between successive standards, so that the sequences were now irregularly timed compared to the regularly timed (isochronous) sequences examined in Experiments 1 and 2. As in the previous two experiments, we compared the same short, medium and long interval (oddball onset) conditions. DAT and the entrainment account predict irregular sequence timing should reduce or possibly even eliminate the effect of oddball onset.

4. Experiment 3

(a) Material and methods

(i) Participants and design

Twenty-two undergraduate students (15 female, 18–22 years, $M = 19.6$, s.d. = 1.3) from Michigan State University with self-reported normal hearing participated in the experiment in return for partial course credit. Participants varied in number of years of formal music training ($M = 2.7$, s.d. $= 2.6$). An additional three individuals completed the experiment, but were not included in the final sample due to inattention to task, non-compliance with task instructions or exceptionally poor performance (relative JNDs $> 75\%$). The design of the experiment was identical to Experiment 1. Three oddball onset conditions (469, 700 and 931 ms) were crossed with four oddball positions (5th, 6th, 7th and 8th) and nine oddball durations (350 ms $\pm$ 0, 5, 10, 15, 20%) in a within-subject design. The key difference from Experiment 1 was that the IOI between standards was no longer fixed at 700 ms, but was variable, resulting in irregularly timed sequences; note, however, that the interval preceding the oddball onset was always fixed at 469, 700 or 931 ms, depending on onset condition. Excluding the interval associated with the oddball onset, sequences still maintained an overall mean IOI of 700 ms between stimulus onsets.

(ii) Stimuli, equipment and procedure

Stimuli, equipment and procedure were the same as Experiment 1, except that the IOI between successive standard tones and the IOI immediately following the oddball tone was variable, while maintaining the same overall sequence duration and average IOI as in Experiment 1 (figure 1*d*). Critically, the set of three possible intervals preceding oddball onset was identical to Experiments 1 and 2 (i.e. oddball onset was 469, 700 or 931 ms). To jitter the timing of the other sequence intervals, while maintaining a mean IOI of 700 ms, 40 irregular timing patterns were created by randomly varying the gap between the offset of each tone and the onset of the next. Offset-to-onset gap lengths were created by randomly sampling from a uniform distribution between 50 and 650 ms and then constraining the last IOI of the sequence to maintain the same sequence duration and mean IOI as Experiment 1. The 40 irregular timing patterns were then randomly crossed with the factors oddball onset, position and duration.

(b) Results and discussion

Figure 4 shows mean DDF as a function of oddball onset for the irregularly timed sequences. Mean relative JNDs are reported in table 1. The repeated-measures ANOVA on DDFs revealed a main effect of oddball onset, $F_{2,42} = 16.31$, $p < 0.001$, $\eta_p^2 = 0.44$. Although the ANOVA on DDFs revealed a main effect of oddball onset, irregularly timed sequences produced less distortion in perceived oddball duration than observed in Experiment 1 with isochronous sequences. Here, the effect of onset was driven primarily by a difference between the early and on-time conditions. Paired-samples *t*-tests revealed no difference in DDFs between the on-time and late conditions, $t_{21} = 1.49$, $p = 0.15$, $d = 0.32$, but a reliable difference between the on-time and early conditions, $t_{21} = -4.62$, $p < 0.001$, $d = 0.99$. Similar to the previous experiments, an ANOVA on JNDs revealed no main effect of oddball onset, $F_{2,42} = 1.5$, $p = 0.23$, $\eta_p^2 = 0.07$. These findings provided mixed support for DAT and an entrainment account. DAT predicts that irregularly timed sequences should reduce or eliminate distortions found with oddballs that occur unexpectedly early and late; this was true for comparison between late and on-time oddballs, but not for the comparison between early and on-time oddballs.

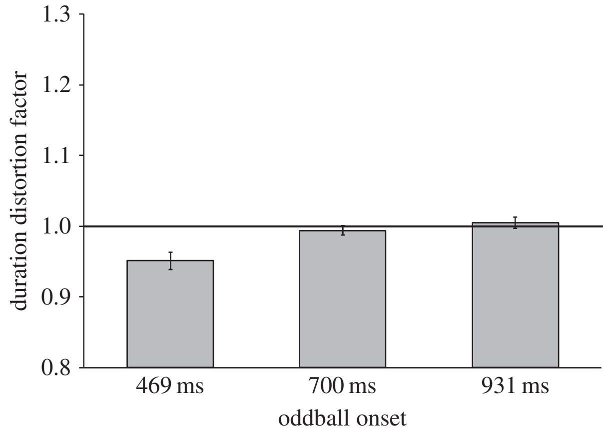

Figure 4. Mean DDF (with standard error bars) for oddballs presented with onsets of 469, 700 and 931 ms for the irregularly timed standards in Experiment 3.

5. General discussion

The study considered the contribution of attentional entrainment to systematic distortions in perceived event duration in the context of an auditory oddball paradigm. Individuals experienced a rhythmic (isochronous) sequence of standard tones and were asked to judge the duration of an embedded oddball tone that differed in pitch from the standard. Predictions of DAT were tested by manipulating the relative temporal onset of the oddball tone; oddballs occurred at time points that were expected (i.e. on time) or unexpected (i.e. early or late) with respect to the extrapolation of an entrained rhythm.

Five main findings emerged. First, in Experiments 1 and 2, there was the least distortion in perceived oddball duration (i.e. duration judgements were most accurate) when the temporal onset of the oddball was on time relative to the entrained rhythm. Second, consistent with DAT predictions and an entrainment account, perceived durations of oddball stimuli were shortened when they arrived earlier than expected, but were lengthened when they arrived later than expected. Third, this pattern of shorter and longer perceived durations as a function of oddball onset held when we controlled for the absolute duration of the interval preceding the onset of the oddball (combined analysis of Experiments 1 and 2). Fourth, adding support to DAT and an entrainment account, irregularly timed (arrhythmic) sequences weakened the onset timing effects. With respect to this finding, it is important to note that reduced distortions with irregular timing were found with late onsets, but not early onsets. Finally, relative JNDs (discrimination thresholds) were not affected by onset timing in all three experiments. This suggests that although attentional entrainment affected the perceived duration of an event, it did not affect the individual's ability to discriminate changes in event duration. The only factor affecting JNDs in this study was the tempo manipulation in Experiment 2; it was harder for individuals to discriminate duration when sequences were presented at a faster tempo.

Results from this study are inconsistent in a number of key respects with past accounts of distortions in perceived duration that have been observed for 'oddball' stimuli in an oddball paradigm (i.e. the oddball effect). First, Tse and co-workers proposed that the unexpected oddball stimulus captures attention, and thereby should be perceived to be longer in duration than it would otherwise, based on the

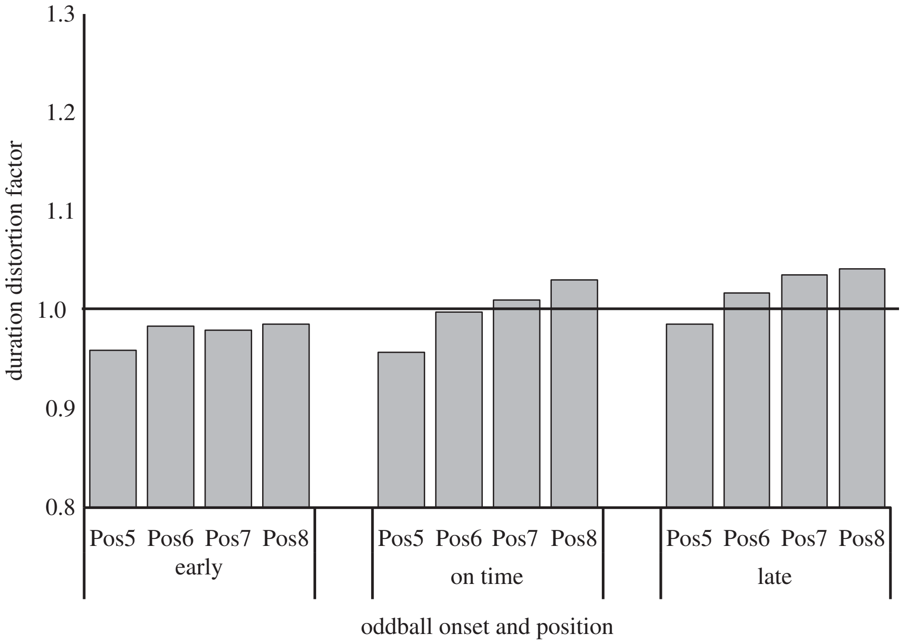

Figure 5. Mean DDF for oddballs presented with an onset of 700 ms in positions 5, 6, 7 and 8. The 700 ms onset was relatively early, on time or late in the context of fast, moderate and slow standard tempo conditions, respectively, of Experiments 1 and 2. Note that there are not enough observations per condition to reliably estimate DDFs separated by both position and onset conditions for each participant, thus the values plotted here represent aggregate DDF estimates, rather than means of individual participant data. As predicted, across onset and rate conditions, there appeared to be an effect of position, such that later positions yielded greater overestimation relative to earlier positions. Further, late oddballs occurring in later sequence positions were perceived to be longer than when presented earlier in the sequence; conversely, early oddballs presented in earlier sequence positions were perceived to be shorter than when presented later in the sequence.

assumption that attentional capture increases the effective accumulation of temporal information [13]. From a mechanistic standpoint, this is realized by an internal clock (pacemaker-accumulator) model of timing [19–21]. From this perspective, early oddballs, if anything, should be surprising and would thus be reasonably expected to capture attention, and be perceived to be longer than oddballs that were on time or late. However, the opposite was observed. Consistent with DAT and the prediction of reduced attention associated with unexpectedly early events, durations of early oddballs tended to be perceived to be shorter rather than longer than on-time oddballs.

One alternative explanation of the oddball effect that has been proposed is that it is an indirect consequence of reduced neural activity in response to the repeated standard stimulus [24,27,30]. According to the repetition suppression/predictive coding view, temporal expansion of an oddball event in an otherwise identical stream of events occurs because the repeated or more generally predictable standard stimulus that precedes the oddball stimulus produces habituation, rather than because the oddball stimulus produces attentional capture. This view assumes that duration is represented by the magnitude of neural response. Thus, because exposure to the repeated standard stimulus produces reduced neural activity, the duration representation for the standard is temporally contracted (i.e. shortened), and an equivalent-duration oddball is perceived as longer in comparison.

Repetition suppression/predictive coding accounts for a number of findings related to distortions in perceived duration observed in the context of an oddball paradigm. Perhaps the strongest support comes from previous studies revealing an effect of oddball serial position on perceived duration, such that oddballs presented in later serial positions are perceived to be longer than oddballs presented in earlier serial positions [28,30]. Repetition suppression/predictive coding predicts a position effect because increasing the number of repetitions of the standard prior to the oddball should produce a greater level of repetition suppression in response to the standard; thus, oddballs in later positions (occurring after more standard repetitions) should be perceived to be longer than oddballs in earlier positions (occurring after fewer standard repetitions). However, with respect to the present data, it is not clear how repetition suppression/predictive coding would be able to account for the observed effect of relative oddball onset timing as the number of standard repetitions preceding the oddball is the same in the early, on-time and late conditions.

In addition to accounting for the effect of onset timing, DAT and the attentional entrainment view also provides an account of the position effect, but goes further than the repetition suppression account by suggesting that there should be an interaction between position and onset. That is, the degree of entrainment is predicted to increase with more repetitions leading to greater temporal expectation for on-time events. Although it was not possible to include position as a factor in the statistical analysis because there were not enough observations by position and onset condition to reliably estimate PSE (and thus, DDF), we were able to consider a position effect and possible interaction with onset by combining the data across participants to obtain aggregate DDF estimates by each position and onset. For this analysis, we combined data across Experiments 1 and 2 so that we could compare early, on time and late onset conditions where the interval preceding the onset of the oddball was always 700 ms. Results for the aggregate position by onset data are shown in figure 5. As predicted by DAT and an entrained attention account, this figure shows both an effect of position and an effect of onset that is larger in later sequence positions than in earlier (i.e. position and onset interact). In general, later positions yielded longer perceived durations than earlier positions and there is a general lengthening of perceived duration as a function of onset (early, on time, late). However, in the earliest sequence position (5th), the effect of onset is virtually absent, but as the sequence continues to unfold in time—enabling greater entrainment—the effect of onset is more robust.

Kim & McAuley [28] recently proposed that the general position effect shares similarities with a variable foreperiod effect and can be productively recast in terms of temporal preparation (see [32] for a review of the foreperiod effect on reaction times; and [33,34] for examples of previous investigations into the relationship of foreperiod and perceived duration). Although the oddball occurs in a different position on each trial, it occurs on every trial, thus its occurrence is temporally predictable. This prediction obeys a hazard function, such that the oddball is more certain to occur at later positions than at earlier positions [32–34]. In line with a temporal preparation account, in Kim & McAuley [28], the time needed to detect and respond to an oddball predicted perceived oddball duration, with faster detection times corresponding to longer perceived durations. In conjunction with the present results, this suggests a broader version of a temporal preparation account of the oddball effect incorporating evidence that rhythmic expectations also guide the temporal allocation of attention and influence perceived duration (similarly to the greater allocation of attention to expected time points observed with foreperiod-like temporal preparation effects in [28]).

In conclusion, the results of this study provide support for DAT and attentional entrainment approaches to perceived duration. Past explanations of distortions in perceived duration in an oddball paradigm do not account for the observed findings. Neither the attentional-capture hypothesis proposed by Tse *et al*. [13] nor the repetition suppression/predictive coding account of Pariyadath & Eagleman [24] predict systematic distortions in perceived duration as a function of the timing of the onset of the oddball relative to the preceding rhythm. Combined with other recent work on the role of temporal preparation in distortions in time perception [28,33,34], the present findings place at least a portion of the locus of distortions in the perceived duration of an oddball stimulus on the increased attention to events that are more expected, rather than on the unexpected nature *per se* of oddball stimuli.

More broadly, this study adds to a growing body of work showing that attentional entrainment (i) occurs across modalities [9] and (ii) plays an important role in speech and language processing, namely in helping listeners segment continuous speech signal into meaningful units [10–12]. With respect to language processing, there is increasing evidence that distal speech rhythm guides listeners' temporal expectations about the perceptual organization of later speech material, influencing how they will segment that material and ultimately what words they hear. One implication of this study for this line of work is that it suggests that listeners' entrainment to speech rhythm has the potential to also distort the perception of duration cues used in the identification of individual speech sounds.

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