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ORIGINAL ARTICLE

Perceived duration of auditory oddballs: test of a novel pitch-window hypothesis

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Abstract

Unexpected oddball stimuli embedded within a series of otherwise identical standard stimuli tend to be overestimated in duration. The present study tested a pitch-window explanation of the auditory oddball effect on perceived duration in two experiments. For both experiments, participants listened to isochronous sequences consisting of a series of 400 Hz fixed-duration standard tones with an embedded oddball tone that differed in pitch and judged whether the variable-duration oddball was shorter or longer than the standard. Participants were randomly assigned to either a wide or narrow pitch-window condition, in which an anchor oddball was presented with high likelihood at either a far pitch (850 Hz) or a near pitch (550 Hz), respectively. In both pitch-window conditions, probe oddballs were presented with low likelihood at pitches that were either within or outside the frequency range established by the standard and anchor tones. Identical 700 Hz probe oddballs were perceived to be shorter in duration in the wide pitch-window condition than in the narrow pitch-window condition (Experiments 1 and 2), even when matching the overall frequency range of oddballs across conditions (Experiment 2). Results support the proposed pitch-window hypothesis, but are inconsistent with both enhanced processing and predictive coding accounts of the oddball effect.

Introduction

Human perception of the duration of events is subject to many distortions. One phenomenon of increasing interest in the past decade has been the tendency for the perceived duration of an unexpected (oddball) event in an otherwise identical stream of standard events to be overestimated in duration (Cai, Eagleman, & Ma, 2015; Kim & McAuley, 2013; McAuley & Fromboluti, 2014; New & Scholl, 2009; Pariyadath & Eagleman, 2007; Pariyadath & Eagleman, 2012; Schindel, Rowlands, & Arnold, 2011; Seifried & Ulrich, 2010; Tse, Intriligator, Rivest, & Cavanagh, 2004; van Wassenhove, Buonomano, Shimojo, & Shams, 2008; van Wassenhove & Lecoutre, 2015). The present article reports two experiments that test a novel pitch-window account of the auditory oddball effect. In both experiments, participants judged the duration of an oddball tone relative to a repeated standard tone, in sequences in which the oddball's likelihood of occurrence and pitch varied independently.

In the typical oddball paradigm, sequences of identical fixed-duration standard stimuli (e.g., circles or tones) are presented with an embedded variable-duration oddball stimulus that is distinguished from the standard stimulus by a difference along some physical dimension (e.g., circle size, tone pitch, see Fig. 1). Participants judge whether the duration of the oddball is shorter or longer than the fixed duration of the standard. Proportions of longer responses at each oddball duration are used to construct psychometric curves for each participant, from which a measure of perceived oddball duration, the point-of-subjective-equality (PSE), is found. PSE is calculated by estimating the oddball duration that corresponds to a response proportion of 50% on the psychometric curve, thus indicating the oddball duration that is perceived to be equivalent to the fixed duration of the standard (i.e., the point of objective equality, or POE). PSE estimates that are longer than the POE indicate underestimation, while PSE estimates that are shorter than the POE indicate overestimation.

The canonical oddball effect in the time domain is the finding that the PSE tends to be shorter than the POE, indicating overestimation of oddball duration. Initial studies reporting an oddball effect in perceived duration observed overestimation of oddball duration by as much as ~36% of

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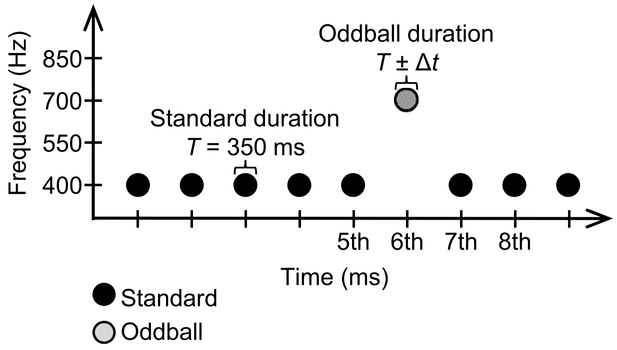

Fig. 1 Diagram illustrating a single trial in the auditory oddball paradigm. Participants heard a sequence of nine tones that included an embedded oddball tone that differed in pitch from the standard and occurred in either the fifth, sixth, seventh, or eighth sequence position. Participants judged whether the variable-duration oddball tone was shorter or longer in duration than the fixed-duration standard tone

the POE for durations > 120 ms. The large magnitude of these effects is likely due, however, to centering the to-be-judged oddball durations in the direction of overestimation (Tse et al., 2004). More recent studies of the oddball effect that have centered to-be-judged oddball durations on the standard duration have found a smaller degree of overestimation, ranging from about 4–18% of POE (Birngruber, Schröter, & Ulrich, 2014, 2015; Cai et al., 2015; Lin & Shimojo, 2017; New & Scholl, 2009; Pariyadath & Eagleman, 2007, 2012; Schindel et al., 2011; Seifried & Ulrich, 2010; van Wassenhove et al., 2008).

Although there has been a tendency to observe overestimation of oddball duration (i.e., PSEs that are shorter than the POE), a multitude of factors has been shown to influence both the direction and magnitude of oddball duration distortions, including attributes of the oddball and aspects of the task structure. Not all studies using an oddball or similar paradigm have observed overestimation (Matthews, 2015; van Wassenhove et al., 2008), especially in the auditory domain (Kim & McAuley, 2013; McAuley & Fromboluti, 2014; van Wassenhove et al., 2008). In general, larger magnitude distortions have been found for visual compared to auditory oddballs in unimodal sequences (Birngruber et al., 2014; Tse et al., 2004). Further, oddballs presented in later sequence positions tend to be perceived to be longer than oddballs presented in earlier sequence positions (Birngruber et al., 2014; Kim & McAuley, 2013; Pariyadath & Eagleman, 2012). The salience of the oddball relative to the standard stimulus presented within a trial (i.e., local context) has also been shown to affect the magnitude of duration distortions, with more salient oddballs (e.g., a moving visual oddball amidst stationary visual standards) sometimes eliciting greater distortion (van Wassenhove et al., 2008). The timing of the onset of auditory oddballs relative to the timing of the onset of the standard stimulus has also been shown to affect duration distortions, with the least oddball duration distortion occurring for oddballs that were ‘on-time’ with respect to the rhythm of the standard stimuli, and early and late oddballs perceived to be shorter and longer, respectively (McAuley & Fromboluti, 2014).

Aspects of the task structure also have been shown to affect duration distortions. For visual oddballs, equality (same/different) judgments generally lead to greater overestimation than comparative (shorter/longer) judgments, though the reverse has been reported for auditory oddballs (Birngruber et al., 2014). Across several studies, the distribution of to-be-judged durations has been shown to affect oddball distortion magnitude, with oddball durations centered in the direction of predicted PSE leading to greater overestimation than oddball durations centered on the POE (Kim & McAuley, 2013; Seifried & Ulrich, 2010; Tse et al., 2004).

Of primary interest in the current research is the degree to which the direction and magnitude of the oddball effect separately depend on (1) the similarity between the oddball and standard stimuli and (2) the oddball’s likelihood of occurrence. The first type of expectation refers to how similar (or different) along some physical dimension a stimulus is from what is expected (e.g., red and black are more distinct than gray and black). The second type of expectation refers to how likely a stimulus is to occur (e.g., if 1 of out of 10 circles in a series is red and the others black, then the red circle has a low 10% likelihood of occurring on a given trial, whereas the black circle is 90% likely). The relative contributions of these two types of expectation—namely, oddball similarity to the standard and likelihood—have often co-varied in past studies or only one of these two factors has been varied (Lin & Shimojo, 2017; New & Scholl, 2009; Pariyadath & Eagleman, 2007; Seifried & Ulrich, 2010; Tse et al., 2004; van Wassenhove et al., 2008; van Wassenhove & Lecoutre, 2015), and thus have not be fully characterized, particularly in the auditory domain.

In the visual domain, several studies have begun to separate the effects of similarity of the oddball to the standard and the oddball’s likelihood of occurrence on the magnitude of duration distortions (Birngruber et al., 2015; Cai et al., 2015; Pariyadath & Eagleman, 2012; Schindel et al., 2011; Ulrich, Nitschke, & Rammsayer, 2006). Manipulations of oddball similarity have generally revealed that the oddball effect increases in magnitude with the degree of stimulus difference between the oddball and the standard. Schindel et al. (2011) varied the angular rotation of an oddball rectangular bar relative to standard rectangular bars. Oddballs were rotated by 0°, ± 15°, or ± 45° (and were additionally distinguished from the standards by being of dimmer luminance). With increasing oddball rotation, overestimation increased linearly from ~ 4.5 to 15%. Pariyadath and Eagleman (2012) similarly varied the degree of angular rotation of an oddball line relative to a standard line from 0° to as much as 90°. Consistent with the results of Schindel et al. (2011), the magnitude of oddball overestimation increased linearly with degree of difference, reaching a maximum of about 13% distortion for 50° rotation.

Manipulations of target likelihood have revealed more mixed results, with low likelihood oddballs only sometimes leading to longer perceived durations than high likelihood oddballs. Ulrich et al. (2006) varied target likelihood so that there were low- and high-likelihood targets in a modified visual oddball paradigm while holding the physical difference between the target (oddball) and standard stimuli constant. For durations in the range of 400–800 ms, they found that low-likelihood targets were perceived to be overestimated to a greater degree (~ 4–12.5%) than high-likelihood targets (~ 1–5%). In contrast, Cai et al. (2015) did not find a significant effect of varying oddball likelihood on perceived duration. In their study, the oddball was a line that was rotated either clockwise or counter-clockwise by 22.5° relative to the repeated standard line. Each oddball type could occur with either 20% or 80% likelihood depending on session and condition (i.e., either a clockwise oddball was presented with 20% likelihood in the same session as a counter-clockwise oddball presented with 80% likelihood, or vice versa). Oddball types were equivalently overestimated regardless of the likelihood of occurrence. At least one past study has further suggested that oddball similarity and likelihood may only affect duration distortions when target/oddball stimuli and standard stimuli are presented in the same spatial position (Birngruber et al., 2015). In sum, past visual studies varying either similarity of the oddball to the standard or its likelihood of occurrence have found that oddballs that are more distinct from the standard tend to be more overestimated than oddballs that are more similar to the standard, with variations in oddball likelihood yielding mixed effects on duration distortions.

Fewer studies have used an auditory paradigm to examine potential effects of oddball similarity and likelihood on perceived duration. One exception is a recent study by Kim and McAuley (2013). In this study, the authors varied the frequency (pitch) difference between the oddball tone and standard tone, while independently varying the oddball's likelihood of occurrence. Participants heard nine-tone sequences comprised of eight identical standard tones and one embedded oddball tone, identified by a different pitch, which occurred in the fifth, sixth, seventh, or eighth sequence position. Oddball tones were either near (e.g., 550 Hz) or far (e.g., 850 Hz) in pitch from the repeated standard tone (e.g., 400 Hz), and each oddball pitch was presented either on 75% or 25% of trials. Results revealed that oddballs farther in pitch from the standard were both perceived to be longer (Experiment 1) and were detected more quickly (Experiment 2) than equivalent-duration oddballs that were nearer in pitch, with a greater difference in perceived duration and detection times between near- and far-pitched oddballs when the oddball pitch was less likely (i.e., the 25% condition). This result demonstrated that the magnitude of duration distortions depended not only on oddball pitch similarity to the standard (i.e., whether the oddball was near or far in pitch), but also on the likelihood with which an oddball type was presented (e.g., whether a far-pitch oddball was 75% or 25% likely). Far-pitch oddballs presented with a 25% likelihood were perceived to be somewhat longer in duration than far-pitch oddballs presented with a 75% likelihood. In contrast, near-pitch oddballs presented with a 25% likelihood were perceived to be shorter in duration than near-pitch oddballs presented with 75% likelihood. In summary, the effect of likelihood was opposite for far-pitch oddballs and near-pitch oddballs. For far-pitch oddballs, low likelihood led to longer perceived duration (and faster detection times), whereas for near-pitch oddballs low likelihood led to shorter perceived duration (and shorter detection times).

Theoretical accounts of the oddball effect

There have been a number of previous explanations of the oddball effect; see Mathews & Gheorghiu, 2016 for a recent review. One account, which we will refer to as the enhanced processing account, attributes overestimation of oddball duration to the oddball stimulus receiving an increased rate of information processing relative to surrounding stimuli; see for example, Tse et al. (2004). In mechanistic terms, this explanation of oddball overestimation rests on the assumption that duration judgments reflect a pacemaker–accumulator process in which some form of pacemaker emits a series of pulses at a particular rate and the accumulation of these pulses determines the judged temporal extent of a stimulus (Church, 1984; Gibbon, 1977; Gibbon, Church, & Meck, 1984; Lejeune, 1998; Meck, 1983; Treisman, 1963). Various factors, such as arousal, have the potential to modulate either the pacemaker rate or the efficiency with which pulses are accumulated—and consequently affect the perceived duration. Thus, the enhanced processing explanation proposes that overestimation of the oddball's duration occurs because there is an increase in the effective rate of pulse accumulation either through a faster pacemaker rate (New & Scholl, 2009; Tse et al., 2004; Ulrich, Nitschke, & Ramsayer, 2006) or greater efficiency of transfer of pulses to the accumulator.

It is important to note here, however, that a related account makes the opposite prediction about perceived oddball duration. Zakay, Block and colleagues have proposed that an attentional gate mechanism modulates perceived duration (pulse accumulation) based on the amount of attention allocated to non-temporal as opposed to temporal properties of a stimulus (Zakay & Block, 1997). Within the attentional gate framework, when more attention is diverted to stimulus properties, less attention is available for temporal processing. This view has been successfully applied in the context of dual-task paradigms, whereby shorter perceived durations have generally been found when concurrent non-temporal tasks divert attention away from timing (Brown, 1985, 1997; Brown & Boltz, 2002; Macar, Grondin, & Casini, 1994; Zakay, Nitzan, & Glicksohn, 1983; and reviewed in Block, Hancock, & Zakay, 2010). The implication of this view is that when non-temporal properties of a stimulus are attention demanding, stimuli will be perceived to be shorter in duration than stimuli with less attention-demanding non-temporal properties. Thus, from an attentional gate perspective, the non-temporal properties of the unexpected oddball divert attention from timing, leading to the prediction that its duration will be under- rather than overestimated.

The finding of longer perceived durations for oddballs that are more different from the standard along some perceptual dimension than oddballs that are less different from the standard (Cai et al., 2015; Kim & McAuley, 2013; Schindel et al., 2011) is consistent with the enhanced processing account based on the assumption that more distinctive oddballs are more perceptually salient than less distinctive oddballs, thereby increasing the amount of temporal information (i.e., number of neural pulses) accumulated over the oddball's temporal extent. Similarly, the finding that less likely oddballs lead to longer perceived duration compared to more likely oddballs (Ulrich et al., 2006) is consistent with the enhanced processing account based on the assumption that more rare (less likely) oddballs capture attention (or otherwise enhance processing) to a greater degree than less rare (more likely) oddballs. A limitation of the enhanced processing account is that it lacks some specificity regarding how gradations in oddball similarity and likelihood affect perceived duration and does not make any clear predictions about how these two factors might interact.

Another proposed explanation of the oddball effect is based on repetition suppression (or more broadly predictive coding). On this view, the oddball effect is an indirect consequence of reduced neural activity (or more efficient coding) in response to the repeated or predictable standard (Cai et al., 2015; Matthews, 2011; Pariyadath & Eagleman, 2007, 2012; Schindel et al., 2011). From this perspective, the magnitude of neural response and corresponding efficiency of coding is a proxy for the representation of duration—with more/less neural response associated with longer/shorter perceived duration. Thus, in a typical oddball paradigm, because repetition (a specific case of predictability) of the standard stimulus reduces neural activity, the representation of the standard duration is temporally contracted (i.e., shortened), and an equivalent-duration oddball, which has not been repeated or is otherwise less predictable than the standard, is perceived as longer in comparison.

Predictive coding successively predicts the graded effect of oddball similarity to the standard on duration distortion magnitudes that has been observed in previous studies (Cai et al., 2015; Schindel et al., 2011), but this view is less clear in its predictions about the effect of oddball likelihood. From a strict repetition suppression standpoint (Cai et al., 2015; Pariyadath & Eagleman, 2007, 2012), likelihood is not predicted to influence duration distortions nor is it predicted to interact with oddball similarity to the standard, since, on a given trial in a typical paradigm, it is the repetition of the standard per se and not session-wide attributes of the oddball such as its likelihood that drive duration distortions. In sum, past theoretical accounts of the oddball effect explain aspects of the independent effects of oddball similarity and likelihood on perceived oddball duration, but neither the enhanced processing nor predictive coding explanations account for the pitch-dependent effect of likelihood reported by Kim and McAuley (2013).

To explain the interaction of pitch and likelihood in the auditory oddball effect, Kim and McAuley (2013) proposed that the pitches of the higher-likelihood oddball and standard tone establish an expected range of pitches for upcoming oddball tones (i.e., a pitch window) over the course of the experimental session. This viewpoint is in part informed by work of Jones et al. on dynamic attending theory, and in particular, the influence of ongoing auditory context (i.e., pitch and temporal structure of auditory sequences) on the development of expectations in pitch in time (Barnes & Jones, 2000; Jones, 1976; Jones & Boltz, 1989; Jones, Johnston, & Puente, 2006; Jones, Moynihan, MacKenzie, & Puente, 2002; Large & Jones, 1999; McAuley & Jones, 2003). Support for the idea that attention is tuned by the pitch and temporal structure of foregoing context comes from the finding of improved pitch discrimination performance for tones embedded in target sequences that match the structure of preceding sequence context (Jones et al., 2006).

In the auditory oddball paradigm, when an oddball tone occurs with high probability, the pitch of the oddball together with the pitch of the repeated standard tone establish a pitch window for "oddness", thereby producing expectations in the listener that guide attentional focus for upcoming oddball events. When an oddball event occurs outside the expected pitch range, it is thus more deviant than an oddball that occurs within the expected pitch range, which makes it quicker to detect. Kim and McAuley (2013) proposed that this faster oddball detection leads to longer perceived duration because it enables earlier initiation of timing of the oddball. Within an internal clock framework, such as scalar expectancy theory (Gibbon, 1977; Gibbon et al., 1984; Treisman, 1963), shorter or longer latency to initiate timing is implemented as a faster or slower closing of the "switch" that allows the accumulation of temporal information over the temporal extent of the stimulus. Faster or slower closing means that temporal information is accumulated for a shorter or longer period of time, directly affecting the perceived duration of the stimulus. Thus, more detectable (i.e., faster to detect) oddballs that occur outside the pitch window are perceived to be longer than equivalent-duration oddballs that occur within the expected pitch range where the oddball is slower to detect.

Consistent with the proposal that latency to initiate a timing process is related to perceived duration distortions, reaction times from a detection experiment of Kim and McAuley (2013) paralleled the pattern of duration distortions observed in the duration judgment experiment. Detection times were faster for far- compared to near-pitch oddballs, with a tendency for low-likelihood, far-pitch oddballs to be detected more quickly than high-likelihood far-pitch oddballs (corresponding to longer perceived durations in the first experiment). In contrast, low-likelihood near-pitch oddballs tended to be detected more slowly than high-likelihood near-pitch oddballs. Across conditions, detection times and perceived duration were reliably correlated, suggesting that both a serial position effect, as well as the pitch effect and interaction with likelihood were possibly related to how quickly listeners initiated timing of the oddball.

In summary, Kim and McAuley (2013) found that oddballs that were a farther pitch distance from a repeated standard were both perceived to be longer in duration and detected more quickly than oddballs that were a nearer pitch distance to the repeated standard. Moreover, low-likelihood far-pitch oddballs were both perceived to be longer and detected more quickly than high-likelihood far-pitch oddballs, whereas low-likelihood near-pitch oddballs were perceived to be shorter and detected more slowly than high-likelihood near-pitch oddballs. The interaction of pitch distance and likelihood led to the proposal that similarity of the oddball relative to the standard together with oddball likelihood determine listener expectations for upcoming (oddball) events, and that these expectations influence perceived duration distortions via differences in detectability.

Current study

One outstanding issue that emerges from Kim and McAuley (2013) is that the low-likelihood oddball differed in pitch across pitch-window conditions. That is, when the low-likelihood oddball was outside the expected pitch range, the low-likelihood oddball was also a higher pitch than when inside the expected pitch range. Thus, whether the low-likelihood oddball occurred inside or outside the expected pitch range co-varied with its pitch. To address this issue in the present study, we conducted two experiments where we matched the pitch and likelihood of the low-likelihood—or, "probe"—oddball tone in two different pitch-window contexts. In both experiments, participants heard nine-tone sequences that consisted of eight standard 350-ms 400-Hz standard tones and a single embedded oddball tone in the 5th–8th position. In Experiment 1, the probe oddball was 700 Hz with a low (25%) likelihood. Half of participants heard an 850-Hz anchor oddball on the other 75% of trials, and half of participants heard a 550-Hz anchor oddball on the other 75% of trials (Fig. 2a). As in Kim and McAuley (2013), participants judged the duration of the variable-duration oddball tone relative to the duration of the repeated fixed-duration standard tone.

The purpose of the anchor oddball was to establish the expected frequency (pitch) range that was wide or narrow. According to the pitch-window hypothesis, the 550-Hz anchor oddball establishes a narrow pitch expectancy range, and the probe oddball falls outside this narrow pitch window. In contrast, the 850-Hz anchor oddball establishes a wide pitch expectancy range, and the probe oddball falls within this wide pitch window. Thus, based on the pitch-window hypothesis, the probe oddball, despite having an identical pitch and likelihood of occurrence in both conditions, is predicted to be perceived to be longer in duration in the narrow pitch-window condition than in the wide pitch-window condition.

The second experiment was similar to the first, but additionally matched oddball pitch range (i.e., the minimum to maximum frequencies experienced by listeners) across pitch-window conditions. To accomplish this, we introduced a secondary probe oddball so that the overall pitch range in both pitch-window conditions was 400–850 Hz (Fig. 2b). Thus, oddballs could take on 1 of 3 possible pitches in Experiment 2, in contrast to Experiment 1 in which there were only two possible oddball pitches. As in the first experiment, a critical probe oddball was 700 Hz and was presented with a low likelihood (12.5% of trials) in both pitch-window conditions. As in the first experiment, the 550-Hz anchor set a narrow pitch expectancy range, which both probes fell outside, while the 850-Hz anchor set a wide pitch expectancy range, which both probes fell within. Thus as in Experiment 1, the critical probe in Experiment 2, despite having an identical pitch and likelihood of occurrence in both conditions, was predicted by the pitch-window hypothesis to be perceived as longer in the narrow pitch-window condition than in the wide pitch-window condition.

Experiment 1

Methods

Participants 36 undergraduate students (27 females, 18–23 years, $M = 19.1$, $SD = 1.2$) from Michigan State University, with self-reported normal hearing, participated in the experiment in return for partial course credit. All participants provided written informed consent prior to participating in the experiment, in accordance with the approved procedures of the Institutional Review Board of Michigan State University. Participants varied in number of years of formal music training ($M = 3.4$, $SD = 4.0$). An additional three individuals completed the experiment, but were not included in the final analysis due to failure to follow instructions or exceptionally poor performance (relative duration discrimination thresholds > 100%).

Design The design of the experiment was a 2 (Pitch Window: wide, narrow) X 2 (Oddball Type: anchor, probe) mixed factorial. Pitch-window condition was a between-subjects factor; oddball type was a within-subjects factor. For both pitch-window conditions, the repeated standard tone was 400 Hz. Participants were randomly assigned to either the wide pitch-window condition in which a 850 Hz anchor oddball occurred on 75% of trials ($n = 19$), or to the narrow pitch-window condition in which a near-pitch 550 Hz anchor oddball occurred on 75% of trials ($n = 17$). In both conditions, a 700 Hz probe oddball occurred on the other 25% of trials.

Stimuli and apparatus Standard stimuli were 350 ms sine tones presented at 400 Hz. The variable-duration oddball was presented in the fifth, sixth, seventh, or eighth sequence position (in order to reduce the temporal predictability of its occurrence) at either the probe pitch, which was always 700 Hz, or the anchor pitch, which was 850 Hz in the wide pitch-window condition and 550 Hz in the narrow pitch-window condition. On each trial, thus, 1/9 of the stimuli was an oddball stimulus. The duration of the oddball took on 1 of 9 values that varied relative to the standard duration, $T = 350$ ms; these were −20%, −15%, −10%, −5%, 0%, +5%, +10%, +15%, and +20%, corresponding to durations of 280, 297.5, 315, 332.5, 350, 367.5, 385, 402.5, and 420 ms, respectively. The inter-onset interval (IOI) between successive stimuli was fixed at 700 ms. Stimuli were generated using MATLAB software (The Mathworks, Inc.) and were presented at a comfortable listening level over

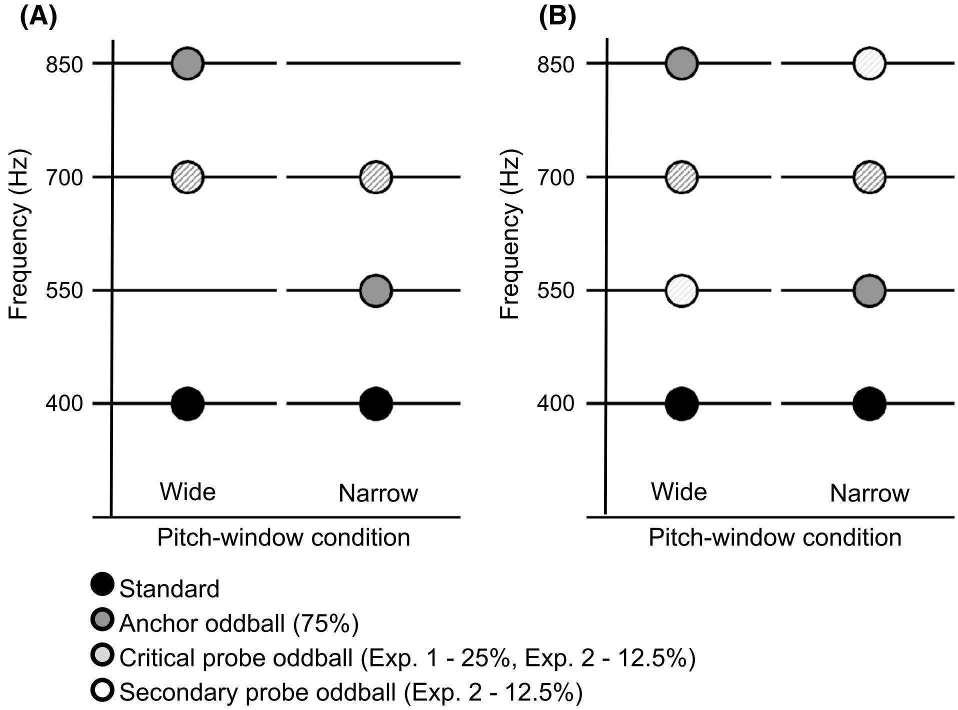

Fig. 2 Diagrams illustrating pitch-likelihood pairings in Experiment 1 (**a**) and Experiment 2 (**b**). In Experiment 1, approximately half of participants heard an 850 Hz anchor oddball on 75% of trials, establishing a wide pitch-window context, while the other half of participants heard a 550 Hz anchor oddball on 75% of trials, establishing a narrow pitch-window context. Participants in both pitch-window conditions heard a 700 Hz probe oddball on the remaining 25% of trials. In Experiment 2, participants in the wide pitch-window condition heard a 75%-likely 850 Hz anchor oddball and two 12.5%-likely probe oddballs, which were a 700 Hz critical probe and a 550 Hz secondary probe. Participants in the narrow pitch-window context heard a 75%-likely 550 Hz anchor oddball and two 12.5%-likely probe oddballs, which were a 700-Hz critical oddball and a 850-Hz secondary probe

Sennheiser HD-280 Pro headphones (Old Lyme, CT). Tone presentation and response collection were controlled by E-Prime 2.0 software (Psychology Software Tools, Inc.) running on a Dell Optiplex 760 series computer with a Creative Sound Blaster Audigy soundcard. Participants responded using a serial button response box.

Procedure A single-trial diagram is shown in Fig. 1. On each trial, participants heard an isochronous sequence of nine tones that consisted of eight 350 ms standard tones and one embedded oddball tone. The duration of the oddball and its position in the sequence (fifth, sixth, seventh, or eighth) varied randomly from trial to trial. Participants judged whether the oddball duration was shorter or longer than the standard duration by pressing one of two labeled buttons on a response box.

Experimental blocks were preceded by a 12-trial practice block consisting of a random presentation of three trials of probe oddball (25% likely) and nine trials of the anchor oddball (75% likely) with the pitch of the anchor oddball dependent on the between-subjects pitch-window condition (wide vs. narrow). Each experimental block consisted of 144 trials, with 36 presentations of the 25% likely probe oddball (4 times per duration) randomly intermixed with 108 presentations of the 75% likely anchor oddball (12 times per duration). Participants completed three experimental blocks, for a total of 432 trials. By oddball type, there were 108 trials presenting the 25% likely probe oddball (12 observations at each duration) and 324 trials presenting the 75% likely anchor oddball (36 observations at each duration). Participants were required to take a 1-min break every 36 trials, and a 2-min break between each block. At the end of the experimental portion, a questionnaire about participant demographics and any strategies used during the experiment was administered. The entire experiment took approximately 90 min.

Data analysis Proportions of *longer* responses were determined for each of the nine oddball durations for each participant in each condition, averaging over oddball sequence positions and experimental blocks (practice trials were not included in analysis). Data were averaged over the four sequence positions to obtain enough observations at each of the nine oddball durations to reliably estimate PSEs and JNDs for each participant in each oddball type and pitch-window condition. To estimate perceived oddball duration, response proportions were used to calculate PSEs using the z-transform method of Macmillan and Creelman (2005) for each participant in each condition. First, response proportions were converted to z-scores by calculating the corresponding inverse probability value from the cumulative normal distribution function, with response proportions of 0 and 1 replaced by $1/(2n)$ and $1-(1/2n)$, respectively, where n is the number of observations. For the 25% likely probe oddball, $n=12$, and for the 75% likely anchor oddball, $n=36$. Next, the best-fit line through the nine points of the psychometric response curve (in z-scored units, the psychometric function is approximately linear) was found using a least-squares method. R^2 measures of goodness-of-fit for the estimated psychometric functions ranged between 0.77 and 0.98 across participants. To assess the stability of the PSE estimates, we compared several alternative methods for estimating PSE. The different psychophysical methods for estimating PSE yielded similar estimates and the same general pattern across conditions (see "Appendix 1").

Based on the best-fit line, PSE is calculated as the duration corresponding to a response of longer 50% of the time and JND is half the stimulus-duration distance between the 25th and 75th percentiles of the psychometric curve, representing a duration discrimination threshold estimate. In line with previous studies of the oddball effect, analyses focused on PSEs to evaluate the predictions of the pitch-window hypothesis. Notably, relative JNDs were on average 8.8% and did not vary appreciately across conditions (see "Appendix 2"). With respect to PSEs, a smaller PSE corresponds to longer perceived duration (and conversely, a larger PSE corresponds to shorter perceived duration). PSEs were subjected to mixed-measures ANOVAs with pitch window as a between-subject factor and oddball type as a within-subject factor. Simple effects analyses were used to interpret significant interactions.

Results and discussion

Figure 3 shows proportions of *longer* responses as a function of oddball duration for the anchor oddballs (Panel A) and the probe oddballs (Panel B) in the wide and narrow pitch-window conditions. Corresponding estimates of PSE for anchor and probe oddballs in the wide and narrow pitch-window conditions are shown in Fig. 4. A 2 (Pitch Window: wide, narrow) × 2 (Oddball Type: anchor, probe) ANOVA on PSE revealed a significant main effect of pitch-window condition, $F(1, 34)=5.10$, $p=.031$, $\eta^2=0.130$, no main effect of oddball type, $F(1, 34)=2.30$, $p=.626$, $\eta^2=0.007$, and, critically, a significant interaction between oddball type and pitch-window condition, $F(1, 34)=10.35$, $p=.003$, $\eta^2=0.233$. The main effect of pitch-window condition revealed that oddballs in the narrow pitch-window condition ($M=344.9$, $SD=20.1$) were perceived to be longer in duration than in the wide pitch-window condition ($M=358.7$, $SD=16.7$), $t(34)=2.26$, $p=.031$, $d=0.75$. As can be seen in Fig. 4, the main effect was driven by the interaction between oddball type and pitch-window condition.

To interpret the interaction, we performed a simple effects analysis comparing PSEs for oddball type across levels of pitch-window condition. This analysis revealed that the main effect of pitch-window condition can be accounted for by a difference in perceived duration of the probe oddballs across the two pitch-window conditions. As predicted by the pitch-window hypothesis, the identical probe oddball presented outside the narrow pitch window ($M=341.3$, $SD=23.3$) was

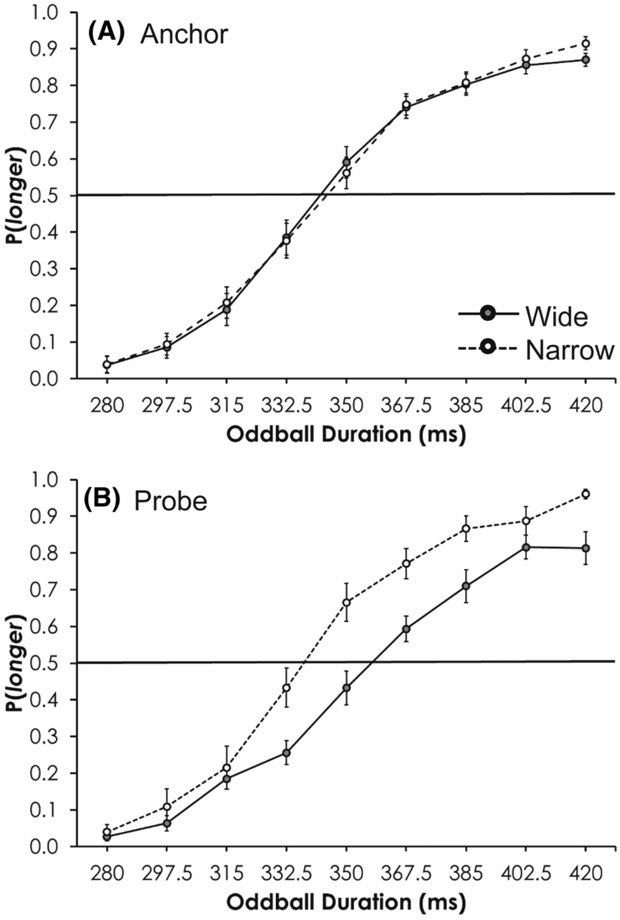

Fig. 3 Experiment 1 mean proportions of *longer* responses with standard error bars as a function of oddball duration for the anchor (**a**) and the probe (**b**) oddballs in the wide pitch-window condition (solid lines) and the narrow pitch-window condition (dashed lines)

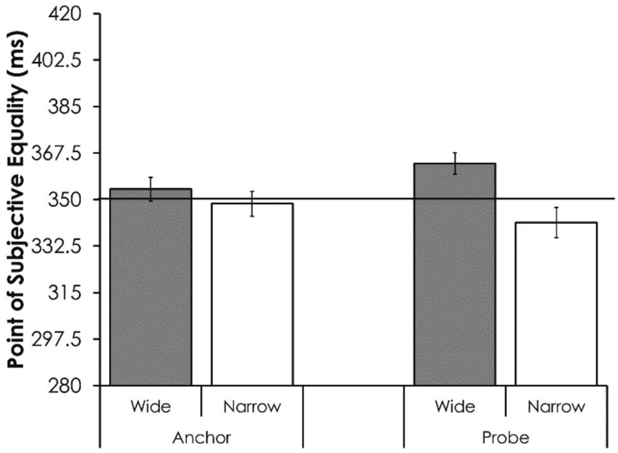

Fig. 4 Experiment 1 mean point-of-subjective-equality (PSE) estimates with standard error bars for anchor oddball (left) and probe oddball (right) for the wide pitch-window condition (shaded bars) and narrow pitch-window condition (white bars)

perceived to be longer than the identical probe oddball presented inside the wide pitch window ($M = 363.6$, SD = 17.6), $t(34) = 3.253$, $p = .003$, $d = 1.09$. Moreover, estimates of PSE for the anchor oddballs in the narrow pitch-window condition ($M = 348.4$, SD = 19.3) and the wide pitch-window condition ($M = 353.9$, SD = 19.7) did not significantly differ, $t(34) = 0.84$, $p = .407$, $d = 0.28$. Support for the pitch-window hypothesis can also been seen in the overlapping psychometric curves for the anchor oddball in Panel A of Fig. 3 and the left-shifted curve for the probe oddball in the narrow pitch-window condition compared to the wide pitch-window condition in Panel B of Fig. 3.

One issue raised by Experiment 1 is that the overall frequency (pitch) range of presented stimuli differed across pitch-window conditions. In the narrow pitch-window condition, participants were presented with tones ranging from 400 Hz (the standard) to 700 Hz (the probe oddball). However in the wide pitch-window condition, participants were presented with tones ranging from 400 Hz (the standard) to 850 Hz (the anchor oddball) with the 700-Hz (probe) oddball in the middle of the range. Thus, the overall frequency range of stimuli co-varied with whether or not the probe oddball was inside or outside the pitch window established by the anchor oddball. In the narrow pitch window condition, the frequency range of all stimuli was 400–700 Hz, whereas in the wide pitch-window condition, the frequency range of all stimuli was 400–850 Hz. Thus, the results of Experiment 1 do not rule out the possibility that in Experiment 1 the critical probe in the narrow pitch-window condition was perceived as longer due to its salience, based on being both relatively rare and "extreme" (i.e., the most distant pitch from the standard experienced by listeners in this condition) compared to the high-likelihood anchor.

To address this issue, in Experiment 2, we added an additional (secondary) probe oddball, which equates the overall range of pitches that listeners experience in the wide and narrow pitch-window conditions, while maintaining the distinction between the wide and narrow pitch-window conditions established by the pitch of the high-likelihood anchor oddball. To do this, we introduced a secondary probe oddball in both pitch-window conditions (see Fig. 1b). In both the wide and narrow pitch-window conditions, participants experienced the same four tone frequencies, which were the 400-Hz standard tone and three oddball frequencies (550 Hz, 700 Hz, and 850 Hz). In the wide pitch-window condition, the 850 Hz oddball was the 75% likely anchor and the 550 Hz and 700 Hz oddballs were the secondary and critical probes, respectively, each occurring with 12.5% likelihood. In the narrow pitch-window condition, the 550 Hz oddball was the 75% likely anchor and the 850 Hz and 700 Hz oddballs were the secondary and critical probes, respectively, each occurring with 12.5% likelihood. As in Experiment 1, the critical probe oddball was 700 Hz in both pitch-window conditions. However, in contrast to Experiment 1, the critical probe's location in the overall frequency range of the stimuli did not co-vary with being inside vs. outside the pitch window established by the 75% likely anchor oddball.

Based on the pitch-window hypothesis, we predicted that the identical, critical probe oddball would be perceived to be longer in duration (corresponding to a smaller estimated PSE) when it occurred within the wide pitch window than when it occurred outside the narrow pitch window, as found in Experiment 1. The introduction of the secondary probe oddball allowed us to test additional predictions of the pitch-window hypothesis. Similar to the critical probe, the secondary probe was predicted to be perceived to be longer in duration when presented outside the narrow pitch window than when presented inside the wide pitch window. Moreover, the addition of the secondary probe allowed us to compare the perceived duration of the critical and secondary probes. We expected the secondary probe in the narrow pitch-window condition to have a longer perceived duration than the critical probe, whereas in the wide pitch-window condition we expected the secondary probe to have a shorter perceived duration than the critical probe. This prediction was based on the reasoning that the secondary probe is farther outside the narrow pitch window than the critical probe, and so is predicted to be perceived to be longer in duration. In contrast, the secondary probe falls farther within the wide pitch window than the critical probe and is more similar to the standard, and thus is predicted to be perceived as shorter in duration than the critical probe.

Experiment 2

Methods

Participants 38 undergraduate students (24 female, 18–23 years, $M=19.2$, $\mathrm{SD}=1.3$) 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 ($M=3.4$, $\mathrm{SD}=4.1$). Six additional individuals completed the experiment, but were not included in the final analysis due to exceptionally poor performance (relative duration discrimination thresholds > 100%).

Design The design paralleled Experiment 1, except that participants were presented with three types of oddballs (anchor oddball, critical probe oddball, and secondary probe oddball) with probe oddball likelihood equal to 12.5%. Participants were randomly assigned to either the wide pitch-window condition ($n=20$) in which the 850 Hz anchor oddball occurred on 75% of trials and the 700 Hz critical and 550 Hz secondary probes each occurred on 12.5% of trials, or to the narrow pitch-window condition ($n=18$) in which the 550 Hz anchor oddball occurred on 75% of trials and the 700 Hz critical and 850 Hz secondary probes each occurred on 12.5% of trials.

Stimuli and apparatus/materials Stimuli, apparatus, and materials were identical to Experiment 1.

Procedure The procedure of Experiment 2 was similar to Experiment 1. To obtain an adequate number of observations in each condition, the experiment was split into three sessions. At the start of the first session, participants were given audio and visual instructions, whereas in the second and third sessions, they were only provided with self-paced visual instructions. All three sessions were otherwise identical.

In each session, participants first completed a 12-trial practice block consisting of a random presentation of 9 trials presenting the 75%—likely anchor oddball and three trials presenting the 12.5%—likely probe oddballs. Each experimental session consisted of 288 trials, which included 36 presentations of each of the 12.5% likely critical and secondary probe oddballs (4 times per duration) randomly intermixed with 216 presentations of the 75% likely anchor oddball (24 times per duration). Participants were required to take a 1-min break every 36 trials. By oddball type, there were 108 trials presenting each of the 12.5% likely secondary and probe oddballs (12 observations at each duration) and 648 trials presenting the 75% likely anchor oddball (72 observations at each duration). At the end of the third session, participants completed a background demographics and strategies survey. Each session took approximately 1 h.

Data analysis. General data analysis procedures were identical to Experiment 1. R^2 measures of goodness-of-fit for the estimated psychometric curves that ranged between 0.77 and 0.97 across participants; see "Appendix 1" for comparison of different methods for estimating PSEs. For the 12.5% likely secondary and critical probe oddballs, $n=12$, and for the 75% likely anchor oddball, $n=72$. Similar to Experiment 1, JNDs were on average 10.4% and did not vary appreciately across condition (see "Appendix 2").

Results and discussion

Figure 5 shows proportions of *longer* responses as a function of oddball duration for the anchor oddball (Panel A), the critical probe oddball (Panel B), and the secondary probe oddball (Panel C) in the wide and narrow pitch-window conditions. Corresponding estimates of PSE for anchor, critical probe, and secondary probe oddballs in the wide and narrow pitch-window conditions are shown in Fig. 6. The 2 (Pitch Window: wide, narrow) × 3 (Oddball Type: anchor, critical probe, distal probe) ANOVA on PSEs showed a main effect of pitch-window condition, $F(1, 36)=5.65$, $p=.023$, $\eta^2=0.136$, a main effect of oddball type, $F(2, 72)=13.46$, $p<.001$, $\eta^2=0.272$, and, critically, a significant interaction between oddball type and pitch-window condition, $F(2, 72)=32.83$, $p<.001$, $\eta^2=0.477$. Overall, oddballs in the narrow pitch-window

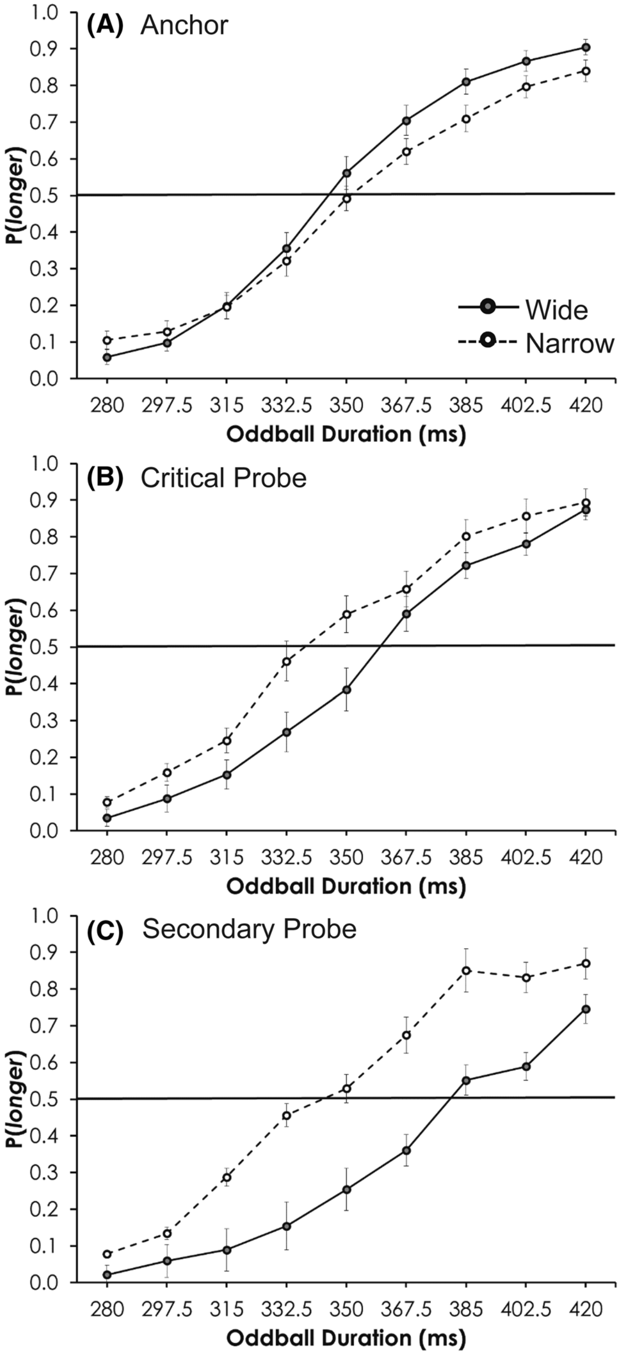

Fig. 5 Experiment 2 mean proportions of *longer* responses with standard error bars as a function of oddball duration for the anchor oddball (**a**), the critical probe oddball (**b**), and the secondary probe oddball (**c**) in the wide pitch-window condition (solid lines) and the narrow pitch-window condition (dashed lines)

condition were perceived to be longer ($M = 350.1$, SD = 22.2), than oddballs in the wide pitch-window condition ($M = 369.0$, SD = 26.2), $t(36) = 2.4$, $p = .023$, $d = 0.77$. As in Experiment 1, the main effects were driven by the interaction of oddball type and pitch-window condition.

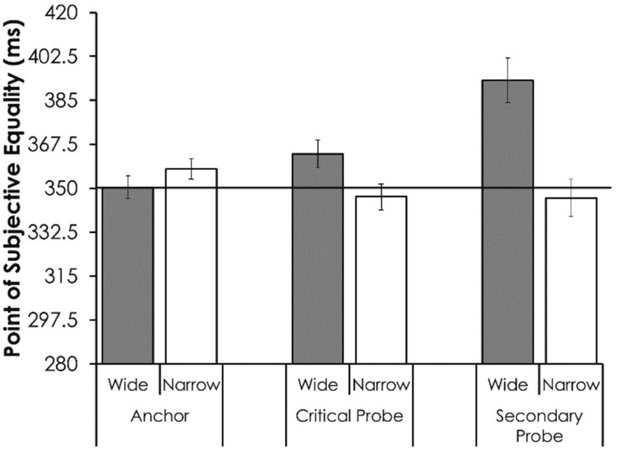

Fig. 6 Experiment 2 mean point-of-subjective-equality (PSE) estimates with standard error bars for anchor oddballs (left), critical probe oddballs (middle), and secondary probe oddballs (right) for the wide pitch-window condition (shaded bars) and narrow pitch-window condition (white bars)

To interpret the interaction, we performed a simple effects analysis examining the effect of oddball type across pitch-window conditions. Consistent with the pitch-window hypothesis, the critical probe oddball, which was identical in both pitch-window conditions, was perceived to be longer in duration when it was presented outside the narrow pitch window ($M = 346.6$, SD = 21.5) than when it was presented inside the wide pitch window ($M = 363.7$, SD = 24.3), $t(36) = 2.3$, $p = .028$, $d = 0.74$. Moreover, the secondary probe oddball was perceived to be longer in duration when it was presented outside the narrow pitch window ($M = 346.1$, SD = 31.4) than when it was presented inside the wide pitch window ($M = 393.0$, SD = 40.2), $t(36) = 4.0$, $p < .001$, $d = 1.28$. In contrast, perceived durations of anchor oddballs in the narrow and wide pitch-window conditions did not differ significantly (narrow, $M = 357.7$, SD = 17.8; wide: $M = 350.2$, SD = 20.0), $t(36) = -1.2$, $p = .236$, $d = 0.39$. Moreover, perceived durations of the critical oddball was significantly longer than the anchor oddball in the narrow pitch-window condition, $t(17) = -3.43$, $p < .01$, but significantly shorter than the anchor oddball in the wide-pitch window condition, $t(17) = 3.64$, $p < .01$. Consistent with the analysis of PSEs, support for the pitch-window hypothesis can also be seen in Fig. 5; panel A shows nearly overlapping psychometric curves for the anchor oddball in the two pitch-window conditions, where Panels B and C show that the psychometric curves for the critical and secondary probe oddballs are left-shifted in the narrow pitch-window condition compared to the wide pitch-window condition.

Finally, we were interested in examining whether probe oddballs more similar to the standard would be perceived to be shorter than probe oddballs that were less similar in pitch to the standard for probes both inside and outside the pitch window. Consistent with the pitch-window hypothesis, when both the critical and secondary probe oddballs were presented inside the pitch window in the wide pitch-window condition, the secondary probe oddball, which was a closer pitch to the standard than the critical probe oddball, was perceived to be shorter in duration than the critical probe oddball, $t(19) = -6.2$, $p < .001$, $d = 1.39$. However, in the narrow pitch-window condition, we observed a different pattern. When both the secondary and critical probe oddballs were outside of the narrow pitch window, but the secondary probe was farther from the standard and anchor than the critical probe, the perceived durations of critical and secondary probes did not differ significantly, $t(17) = 0.13$, $p = .9$, $d = 0.03$.

In sum, the results of Experiment 2 replicate and extend the findings of Experiment 1, offering further support for the pitch-window hypothesis. Critical probe oddballs, which had an identical pitch and likelihood of occurrence across pitch-window conditions, were perceived to be longer in duration when presented outside the narrow pitch window than when presented inside the wide pitch window. Moreover, the same pattern of distortion was found for the secondary probe oddball. Thus, both critical and secondary probes were perceived to be relatively longer in duration when presented outside an expected frequency range (i.e., pitch window) established by the standard and high-likelihood anchor oddball than when presented within the expected frequency range. Critical and secondary probe oddballs differed in perceived duration based on their relative distance from the standard when they fell within the pitch-window, but not when they fell outside the pitch window. In contrast, the perceived duration of the 75% likely anchor oddballs did not differ across pitch-window conditions.

The lack of difference in perceived duration of anchor oddballs across pitch-window conditions combined with the presence of a difference in perceived duration of secondary probe oddballs across pitch-window conditions rules out an explanation of distortion based on purely local context effects—i.e., the relative salience of the oddball compared to the standards on a single trial. If only local context determined oddball duration distortion, then the comparison of anchors across pitch-window conditions should have yielded equivalent results to the comparison of secondary probes across pitch-window conditions (i.e., anything farther in pitch from the standard should have been perceived to be longer). Instead, we found that tones presented at 850 Hz and 550 Hz, when presented with high likelihoods as anchor oddballs, were equivalently distorted across pitch-window contexts, whereas perceived duration of tones at those same two pitches, when presented with low likelihoods as secondary probe oddballs, were relatively more or less distorted depending on context.

Aspects of the present results are also consistent with explanations that consider anchoring of psychophysical judgments based on stimulus statistics, such as adaptation-level theory (Helson, 1964) and range-frequency theories (Parducci, Perrett, & Marsh, 1969). In brief, adaptation-level theory states that participants judge stimulus values relative to an internal norm (or adaptation level) that is based on past experience (mean value of stimuli). Similarly, range-frequency theory states that stimulus judgments are biased by the overall range and frequency of stimulus values experienced (distribution of stimulus values). Thus, both theories describe how judgments are affected by experimental context (stimulus statistics). From this perspective, the adaptation level for pitch (statistical frequency average) is more similar across conditions in Experiment 2 than in Experiment 1, leading to the prediction that the difference in perceived duration of critical probes in wide compared to narrow pitch-window conditions should be smaller in Experiment 2 than in Experiment 1. Consistent with this possibility, we found a slightly smaller difference in perceived duration of critical probes across conditions in Experiment 2 (16.4 ms) than in Experiment 1 (22.3 ms). However, although adaptation level accounts can describe aspects of the current results, an adaptation-level account does not offer an explanation for why or precisely how stimulus statistics in one dimension (e.g., pitch) should distort judgments in another dimension (i.e., time). The pitch-window hypothesis, in contrast, proposes an explanation whereby the tuning of a central mechanism, i.e., attention, by pitch context leads to systematic distortion in perceived duration.

General discussion

Two experiments tested a novel pitch-window hypothesis as an explanation for the auditory oddball effect, independently varying the frequency (pitch) similarity of the oddball to the standard and the oddball's likelihood of occurrence. High-likelihood anchor oddballs together with the standard were used to establish either a wide or narrow expected frequency range for the oddball (i.e., a pitch window). Identical low-likelihood probe oddballs were presented either outside the narrow pitch window or inside the wide pitch window. Consistent with the pitch-window hypothesis, Experiment 1 revealed that identical, 700 Hz, 25%-likely probe oddballs were perceived to be longer when they occurred outside the narrow pitch window than when they occurred inside the wide pitch window.

Experiment 2 controlled the overall frequency range of the oddball tones across pitch-window conditions and found the same general result. The critical 700 Hz, 12.5%-likely probe oddball was perceived to be longer when it occurred outside vs. inside the pitch window. Similarly, a 12.5%-likely secondary probe oddball was perceived to be longer in duration when it occurred at 850 Hz outside a narrow pitch window than when it occurred at 550 Hz inside a wide pitch window. Comparing 12.5%-likely critical and secondary probes additionally revealed that inside the wide pitch window when the 550-Hz secondary probe was closer in pitch to the standard than the 700-Hz critical probe, it was perceived to be shorter in duration. However, outside the narrow pitch window when the 850-Hz secondary probe was farther in pitch from the standard than the 700-Hz critical probe, perceived durations of the critical and secondary probes did not differ. Finally, the 75%-likely anchor oddball, which was 550 Hz in the narrow pitch-window condition and 850 Hz in the wide pitch-window condition, did not differ in perceived duration across conditions in either experiment, despite differing in its pitch distance from the standard.

Results of the present study are inconsistent with enhanced processing explanations of the oddball effect, which would predict a main effect of pitch distance, such that more salient oddballs that are more different from the standard should capture attention to a greater degree and thus be perceived to be longer in duration than less salient oddballs, regardless of pitch-window condition. Note that from an enhanced processing perspective, the 850-Hz anchor oddball in the wide pitch-window condition should be perceived to be longer than the 550-Hz anchor oddball in the narrow pitch-window condition, but the perceived duration of the 700-Hz (critical) probe oddball, which is identical in both pitch-window conditions, should not be perceived to differ in duration across conditions. We found the opposite in both experiments. The two anchor probes, which differed from each other in pitch distance from the standard, were perceived to be equivalent in duration, whereas the critical probe, which was identical across conditions, was perceived be longer in duration in the narrow pitch-window condition than in the wide pitch-window condition.

With respect to likelihood, the enhanced processing account predicts that rarer, low-likelihood events will elicit longer perceived duration than high-likelihood events, as has been observed previously in studies using a visual paradigm (Birngruber et al., 2015; Ulrich et al., 2006). If this were the case, then we would have expected low-likelihood probe oddballs to have longer perceived duration than anchor oddballs. This was not consistently observed. In Experiment 1, there was no main effect of oddball type (i.e., effectively, no difference attributable to likelihood alone), whereas in Experiment 2, there was a main effect of oddball type. Comparing oddballs matched in pitch but differing in likelihood—for example, the 850 Hz, 12.5%-likely secondary probe in the narrow pitch window vs. the 850 Hz, 75%-likely anchor in the wide pitch window—revealed shorter perceived duration of the low-likelihood secondary probe than the high-likelihood anchor, opposite to the predictions of an enhanced processing account. Moreover, inconsistent with the view that the oddball receives enhanced processing in the form of increased arousal (Ulrich et al., 2006), we found that duration discrimination thresholds were not appreciably different across conditions (see "Appendix 2").

Results of the present study are also at odds with predictive coding/repetition suppression accounts, which predict that perceived oddball duration should increase monotonically with degree of oddball difference from the standard. Indeed, we found the opposite of what would predicted by this account. Anchor probes that differed in pitch distance from the standard across conditions were equally distorted, whereas critical probes that were identical across conditions differed in distortion depending on pitch-window context. Specifically, 850-Hz and 550-Hz anchor probes that were farther from or closer to, respectively, the 400-Hz standard did not differ in perceived duration. However, identical 700-Hz (critical) probes were perceived be longer in duration in the narrow pitch-window condition than in the wide pitch-window condition.

A general limitation of the enhanced processing and predictive coding theories applied to the results of the present study is that they focus on local context—that is, the effects of expectations based on a single trial, such as attentional capture by the salient oddball or habituation to the repeated standard. Unlike the pitch-window hypothesis, enhanced processing and predictive coding theories do not take into account potential effects of global context—that is, the effect of expectations that form over the longer timespan of an experimental session—on oddball perceived duration. As such, neither enhanced processing nor repetition suppression accounts predict the observed interactions between oddball similarity and likelihood. Although the observed results are consistent with past descriptions of contextual effects on psychophysical judgments such as adaptation-level theory (Helson, 1964), such theories do not make predictions about the influence of stimulus statistics in the frequency domain on judgments in another domain (e.g., duration).

In contrast, the pitch-window hypothesis tested herein proposes that over an experimental session, which constitutes a global context, a high-likelihood oddball along with the repeated standard establish a pitch expectancy window. On each trial, these dynamically tuned expectancies guide attentional focus in pitch and time for upcoming oddball events. The nature of oddball duration distortion depends on the relationship of perceptual features of the oddball to this expectancy window. In the auditory modality, oddball pitches that fall outside of the pitch expectancy window are expected to be perceived as more deviant, to therefore be more detectable, and are consequently predicted to be perceived as longer in duration than oddball pitches falling within the pitch expectancy window.

From a dynamic attending perspective (Jones, 1976; Jones & Boltz, 1989; Jones, Johnston, & Puente, 2006; Jones, Moynihan, MacKenzie, & Puente, 2002; Large & Jones, 1999; McAuley & Jones, 2003), this global context takes the form of peaks in attentional energy that are entrained by stimulus properties (frequency, timing), producing expectations for future events that emerge over time. There is some past support for temporal entrainment on each trial (i.e., based on local context) in an auditory oddball paradigm affecting duration distortions (McAuley & Fromboluti, 2014). In this study, the authors found that oddballs that occurred unexpectedly early or late relative to the regularly timed standards were more distorted than on-time oddballs. The present finding that pitch-window context influences duration distortions extends this past result in two ways. First, results are consistent with dynamic tuning of attentional scope by perceptual, in addition to temporal, characteristics of stimulus sequences (i.e., narrow tuning in the narrow pitch-window context and wide tuning in the wide pitch-window context). Second, the present results support the view that global, session-wide context plays a role in tuning attention.

The present results provide further insight into the relationship between expectation and distortions in perceived duration. Several recent studies have described oddball duration distortion as resulting from a combination of "top-down" and "bottom-up" effects (Birngruber et al., 2018; Lin & Shimojo, 2017; Matthews 2011, 2015; Matthews & Gheorghiu, 2016; Nazari, Ebneabbasi, Jalalkamali, & Grondin, 2018). Across several studies, Matthews et al. used a two-stimulus duration judgment task akin to the oddball paradigm in which the first stimulus was a standard and the second stimulus was a judged, variable-duration target. The likelihood of whether the target was a repeat of the standard or a novel stimulus varied across conditions to influence expectations. Both bottom-up, immediate repetition and top-down, repetition likelihood manipulations influenced perceived duration. Immediate repetition was found to shorten perceived duration as predicted by repetitions suppression. However, increased expectation for a repeated stimulus based on repetitions being more likely was found to lengthen perceived duration (when it was more likely that the target would be a repeat of the standard than a novel image, perceived duration was longer). Birngruber et al. (2018) similarly found that top-down expectation lengthened perceived duration. In this study, participants vocalized an expectation for which of two stimuli the target stimulus would be, and found that when the target stimulus matched the self-generated expectation, perceived duration was longer than when the target stimulus differed from the self-generated expectation. This and similar findings of increased expectation leading to lengthened perceived duration have been interpreted from the perspective of top-down and bottom-up processing contributing uniquely and in potentially opposing ways to duration distortion.

Matthews and Meck (2016) describe a "processing principle" as a unifying explanation of the sometimes contradictory effects of repetition and expectation on perceived duration (Matthews & Gheorghiu, 2016)—e.g., consistent with repetition suppression, more repetitions of a standard leads to shorter standard duration and thus longer oddball duration (Pariyadath & Eagleman 2012); yet increased expectation when repeats are common in an oddball-like duration judgment task leads to shorter target duration (Matthews, 2011; 2015). According to this account, perceived duration of a stimulus depends on the strength of its perceptual representation. Stimuli that are easier to process (louder, brighter, more vivid in some way) have lengthened subjective duration. From this view, bottom-up factors such as properties of the stimulus influence the signal strength of the input signal. Top-down factors such as selective attention modulate input. Memory also modulates the strength of a perceptual representation by facilitating or impairing information extraction from the input signal. As applied to the oddball paradigm, immediate repetition is a low-level, bottom-up effect that results in shortened perceived duration for the more expected, standard stimulus. In contrast, longer-term expectations based on factors such as repetition likelihood (Matthews & Gheorghiu, 2016), self-generated expectations (Birngruber et al., 2018), cues (Lin & Shimojo, 2017), or prior experience (Nazari et al., 2018) represent top-down effects that result in lengthened perceived duration when a stimulus is more expected. From this perspective, pitch attunement in the present study could be considered to be a combination of bottom-up and top-down factors, as attention is guided or tuned implicitly by characteristics of not only the physical stimuli on a given trial but the overall context that emerges over the experimental session.

One question that emerges from this work is why perceived duration of critical and secondary probes did differ when presented within the established pitch expectancy range, but did not differ when both were presented outside of the established pitch expectancy range. One possibility is that in the wide pitch-window condition, attention is tuned broadly, and so similarity of the oddball to the standard influences duration distortions (all pitches inside the pitch expectancy range fall within the scope of attention). In contrast, in the narrow pitch-window condition, attention is tuned narrowly, and anything beyond the boundary for oddness established by the high-likelihood oddball is perceived as categorically odd (that is, pitches outside the pitch expectancy range fall outside of the scope of attention and thus are not as well-differentiated from each other as pitches that fall inside). Converging support for this possibility from another type of task comes from a study by Jones et al. (2006). In this study, the authors found better target pitch discrimination performance for near-pitch than far-pitch targets in a wide pitch context, but no difference in pitch discrimination performance for near- and far-pitch targets in a narrow pitch context.

Another question that emerges is whether the effect of pitch-window condition on the perceived duration of the secondary probes can be accounted for by absolute differences in pitch across conditions as—unlike the critical probe—the secondary probe differed in pitch across pitch-window conditions. However, if the effect of pitch-window condition on the perceived duration of secondary probes is driven by the pitch difference of the secondary probes, then the anchors should have also differed in perceived duration across pitch-window conditions, since anchors were matched in pitch to the secondary probes (narrow: anchor 550 Hz, secondary probe 850 Hz; wide: anchor 850 Hz, narrow 550 Hz). This was not the case. Perceived duration of anchors in the wide and narrow pitch-window conditions did not significantly differ. Moreover, since likelihood was fixed across oddball type (both 850-Hz and 550-Hz anchors were 75% likely, while both 850-Hz and 550-Hz secondary probes were 12.5% likely), the interaction of oddball type and pitch-window condition cannot be due to a co-variation of pitch and likelihood. Thus, the significant difference in perceived duration of secondary probes across pitch-window conditions supports the prediction of the pitch-window hypothesis that the relationship of the secondary probe to the pitch window (inside vs. outside) drives the observed differences in perceived duration.

Kim and McAuley (2013) proposed that one possible mechanism whereby pitch-window context influences perceived oddball duration may be variation in how quickly individuals are able to detect and initiate timing of oddball stimuli in different contexts. Pitch attunement associated with the establishment of a pitch expectancy range affects detectability of the oddball, with oddballs outside of an expected frequency (pitch) range being detected more quickly than oddballs within an expected range. Faster oddball detection leads to faster initiation of timing in response to the oddball's onset, corresponding to longer perceived duration. This proposal is based on finding a consistent relationship between detection times and perceived duration as a function of oddball pitch distance, likelihood, and sequence position by Kim and McAuley (2013).

Several studies using electroencephalography (EEG) provide converging support for the proposal that earlier timing initiation leads to longer perceived duration (Bendixen, Grimm, & Schröger, 2005; Herrmann, Henry, Fromboluti, McAuley, & Obleser, 2015; Ng, Tobin, & Penney, 2011). Across several studies, larger amplitude early ERP components such as N1 or P2, which have been proposed to index an orienting or detection process, have been found for events perceived to be longer in duration. Bendixen et al. (2005) found a larger N1 response for tones judged to be long than for tones judged to be short, despite the tones having effectively identical duration. Ng et al. found a significant positive correlation between N1–P2 peak-to-peak amplitude and mean CNV amplitude, which has been proposed to reflect temporal accumulation within an internal clock framework (Macar, Vidal, & Casini, 1999), leading them to propose that N1–P2 peak-to-peak amplitude is a marker of timing initiation. Herrmann et al. (2015) further found that experimental context modulates N1 and P2 responses, such that these responses were greater for a "moderate" frequency oddball (parallel to our critical probe) when presented in a small-change context (equivalent to our narrow pitch window) compared to when it was presented in a large-change context (equivalent to our wide pitch window).

This perspective suggests that one potentially promising line of future research is to use EEG to examine the relation between oddball detection latencies, ERP responses, and perceived duration. Based on the pitch-window hypothesis and results of past ERP studies, we would predict (1) larger N1 response to more detectable oddballs (i.e., probes in the narrow pitch-window condition) and (2) a correlation between N1 response and perceived duration, such that larger N1 response and shorter latencies would correspond to longer perceived duration (i.e., shorter PSEs). Alternatively, finding a correlation between a later P3 response and perceived duration would potentially support an arousal account of oddball duration distortion. This possibility would be consistent with recent work examining the relationship between the late posterior P3 and target overestimation in an oddball-like task in which participants judged the duration of target stimuli relative to the duration of standard stimuli (Ernst et al., 2017). Ernst et al. (2017) found that P3 amplitude was larger for targets than standards, and further that larger P3 amplitude was predictive of greater temporal overestimation of a target. They propose that the common mechanism underlying both increased P3 amplitude and duration overestimation is increased release of norepinephrine, a neural counterpart of arousal.

Another potentially fruitful line of future work is to consider how the pitch-window explanation of the auditory oddball effect might be broadened to make predictions about the visual oddball effect. Along these lines, we propose a general perceptual window hypothesis whereby over the course of an experimental session, high-likelihood oddball and standard events establish an expectancy window for upcoming (oddball) events. Based on this hypothesis, low-likelihood oddballs that are outside the perceptual window are predicted to have a longer perceived duration than low-likelihood oddballs that are inside the perceptual window. Testing this hypothesis using a visual oddball paradigm thus would require, analogous to the present study, introducing at least two types of oddballs differing from each other in both similarity to the standard and likelihood, and simultaneously varying both similarity and likelihood (past studies using a visual paradigm have varied either oddball similarity *or* likelihood).

Building off past studies, either angular rotation (Pariyadath & Eagleman, 2012; Schindel et al., 2011) or spatial distance (Birngruber et al., 2015; New & Scholl, 2009) of a visual oddball relative to the standard might be manipulated as visual analogues to pitch distance. For example, using line/rectangular bar stimuli, a high-likelihood anchor oddball might be rotated either 15° or 45° relative to standard orientation to establish either a narrow or wide expectancy window, respectively. The low-likelihood probe oddball would be rotated 30°, thus occurring either outside of the narrow expectancy window when paired with the 15° anchor oddball, or inside the wide expectancy window when paired with the 45° anchor oddball. The perceptual window hypothesis predicts that perceived duration of the probe oddball will be longer when it occurs outside of the narrow window than when it occurs within the wide window. A similar logic applies to variation in spatial distance.

Conclusion

Two experiments tested a novel pitch-window explanation of the auditory oddball effect. Consistent with the pitch-window hypothesis, low-likelihood oddballs of identical pitch distance from a repeated standard tone were perceived to be longer in duration when presented outside of a narrow pitch window established by a high-likelihood oddball than when presented inside a wide pitch window. Neither pitch distance nor likelihood alone affected perceived oddball duration. Anchor oddballs equivalent in likelihood but differing in pitch distance from the standard did not vary in perceived duration. Moreover, perceived duration of anchor and secondary probe oddballs with the same pitch but different likelihoods depended on their relationship to the pitch window. The present results are inconsistent with both enhanced processing and predictive coding explanations of the oddball effect. One potentially promising line of future work is to consider how the pitch-window explanation of the auditory oddball effect might be broadened in the form of a perceptual window hypothesis to make predictions about the visual oddball effect. Based on a general perceptual window hypothesis, low-likelihood oddballs that are outside the perceptual window are predicted to have longer perceived durations than low-likelihood oddballs that are inside the perceptual window.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

Ethical approval All procedures were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards.

Informed consent Informed consent was obtained from all individual participants included in the study.

Appendix 1

Point-of-subjective-equality (PSE) estimates in milliseconds for Experiment 1 and 2 comparing the z-transform method (based on individual vs. aggregate psychometric curves), probit analysis using maximum-likelihood estimation (IBM Corp. Released 2017. IBM SPSS Statistics for Windows, Version 25.0. Armonk, NY: IBM Corp.), and the trimmed Spearman–Karber method (Hamilton, Russo, & Thurston, 1977, 1978; Miller & Ulrich, 2004; Stone, 2015) corresponding to columns labeled Z-Ind, Z-Agg, Probit and TSK, respectively. The different psychophysical methods yielded similar PSE estimates and the same general pattern across conditions.

Oddball type	Pitch window	Experiment 1				Experiment 2			
		Z-Ind	Z-Agg	Probit	TSK	Z-Ind	Z-Agg	Probit	TSK
Anchor	Wide	353.9	351.7	349.4	346.6	350.2	350.4	349.3	349.3
	Narrow	348.4	349.8	348.1	347.3	357.7	356.6	356. 2	358.9
Critical probe	Wide	363.6	363.6	362.4	359.8	363.0	362.3	361.8	363.9
	Narrow	341.3	343.9	342.1	340.5	346.6	346.6	345.5	347.3
Secondary probe	Wide	–	–	–	–	393.0	385.2	385.2	387.1
	Narrow	–	–	–	–	346.1	347.3	346.1	346.1

Appendix 2

Mean relative just-noticeable differences (JNDs), expressed as a percentage, as a function of oddball type and pitch window for Experiment 1 (left column) and Experiment 2 (right column). Standard deviations are shown in parentheses.

Oddball type	Pitch window	Relative JND %	
		Experiment 1	Experiment 2
Anchor	Wide	8.7 (3.9)	8.5 (3.3)
	Narrow	8.4 (4.1)	12.2 (8.4)
Critical probe	Wide	9.9 (3.1)	9.7 (3.4)
	Narrow	8.3 (2.3)	10.2 (3.4)
Secondary probe	Wide	–	11.9 (3.8)
	Narrow	–	10.1 (3.2)

Relative JND estimates shown here are based on full data set for anchors and probes. JNDs in the 75% likelihood (anchor oddball) condition were also estimated by randomly sampling observations so that the number of sampled observations matched the number of observations in the 25% likelihood (Experiment 1—critical probe oddball) or 12.5% (Experiment 2—critical and secondary probe oddball) conditions to eliminate potential estimation biases associated with differences in the number of observations across conditions (e.g., Hautus, 1995). Estimates of JNDs for anchor oddballs using matched number of observations were similar to estimates based on the full data set

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