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How Musical Oddballs Warp Psychological Time

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How Musical Oddballs Warp Psychological Time

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by

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Abstract

Oddballs—low-probability, attention-capturing expectancy violations—are judged as longer than non-oddballs, but are temporal intervals that *contain* oddballs judged as longer than those that do not? In 2 experiments, we tested competing model predictions using a novel and covert measure of subjective duration—musical imagery reproduction. Participants verbally estimated and reproduced with musical imagery repeated, coherent, or incoherent familiar or unfamiliar chord sequences (3.5 s, 7 s, or 12 s) that either did or did not contain dynamic auditory oddballs. Participants verbally estimated repeated chord sequences that contained oddballs as shorter than those that did not, but reproduced with musical imagery incoherent chord sequences that contained oddballs as longer than those that did not. These findings suggest that (a) intervals that contain attention-capturing, high-priority events are judged as shorter than those that do not when people are engaged in relatively temporal information processing, but as *longer* than those that do not when people are engaged in relatively *nontemporal* information processing, and (b) temporal and nontemporal information processing are interdependent. These results support the resource allocation model of short interval time estimation. We discuss implications for attention- and memory-based models, dynamic attending theory, and the ongoing debate about the mechanisms driving the temporal oddball illusion.

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Introduction

Psychological Time

Psychological time is a puzzling concept. How can something as illusory and intangible as time play such a critical role in our lives? This question has mystified philosophers for ages. Relatively recent empirical discoveries suggest that psychological time is a cognitive construction based on perceived and remembered change (Bertotti & Easthope, 1978; Block, 1990; Fraisse, 1963). Change can characterized by continuous or discrete, and sensory or organismic, events (Poynter, 1989). People can track continuous sensory events like planet orbits to measure time's passage on the scale of years, or discrete sensory events like clock ticks, finger taps, and musical beats to measure time's passage on the scale of seconds. We cannot perceive time, itself, but we can form representations of it.

Information Processing

Psychological time is as illusory as it is susceptible to distortion. Block (1990) articulated four overarching factors that work together to distort psychological time: (1) individual differences, (2) the type of time judgment being made about a temporal interval, (3) the content that fills that interval, and (4) the type of information processing in which people engage during that interval.

Examples of individual differences include species, age, sex, cultural background, and personality. Examples of types of time judgments include order, succession, and duration. By "the content that fills an interval," Block (1990) means everything that occurs during a given interval of time. This might include many types of events and processes. Some are internal—thoughts, feelings, neurological activity—and some are external, like tastes, lights, smells, and other sensory stimulation. Furthermore, these events and processes can have characteristics that vary in quantity, complexity, structure, and predictability—in how many there are, how complex they are, how they are organized, and the degree to which they confirm or violate expectations.

The type of information processing in which people engage during an interval can, for instance, be relatively temporal or nontemporal. People engage in relatively temporal information processing when attending to temporal information, such as the ticks of a clock, or the rhythm of a song. On the other hand, people engage in relatively nontemporal information processing when attending to nontemporal information, such as the color of a clock, or the loudness of a song.

Everyday stimuli include both temporal and nontemporal information. Speech, for example, is characterized by temporal information, such as the length of words and inter-onset intervals (IOI; the durations between event onsets), or the rhythmic stress beats of sentences (Allen, 1972). But speech is also characterized by nontemporal information, ranging from vocal timbre to pitch intervals (Boltz, 1999). Both temporal and nontemporal information affect the perception of speech stimuli (Grosjean, 1980).

In music, the relationship between temporal and nontemporal information is underscored. Music consists of temporal information—rhythms change over time, and the orderings of notes change over time. Plenty of nontemporal information exists, as well, such as timbres, amplitudes, pitches, and pitch contours. The ways in which nontemporal information is temporally organized in music is vital. Temporal information plays a key role in the perception of nontemporal properties, despite the fact that these nontempora properties are, themselves, nontemporal (Rosen, 1992).

Attending to temporal information can mean focusing on the rhythm of your favorite song, or simply tracking the passage of time (e.g., by counting seconds, foot taps, heart beats, or exhalations). People engage in relatively temporal information processing when researchers explicitly draw people's attention to the passage of time, or when researchers present people with stimulus sequences that are structured in predictable ways—predictable event structures are processed relatively efficiently and free attentional resources to monitor the passage of time.

On the other hand, attending to relatively nontemporal information can mean focusing on the texture of your favorite shirt, or doing things that distract you from noticing the passage of time. People engage in relatively nontemporal information processing in time estimation experiments where researchers intentionally avoid stating duration, aiming to prevent people from noticing, attending to, or monitoring the passage of time. People also engage in nontemporal information processing when presented with stimuli featuring unpredictable event structures. Unpredictable event structures consume attentional resources and distract people from tracking, or even noticing, the passage of time.

Boltz (1998) investigated the role of temporal and nontemporal information processing on subjective duration in the context of music. Boltz manipulated whether melodies were structurally coherent or incoherent—whether or not the temporal information (rhythms) and nontemporal information (pitches) of the melodies were compatible. She manipulated the degree to which people were engaged in relatively temporal or nontemporal information processing by instructing them to either attend to the melodies' pitch properties (nontemporal information), total durations (temporal information), or both; another group was given no attending instructions.

Boltz (1998) found that incoherent melodies were judged as longer than coherent ones when people were engaged in relatively nontemporal information processing (pitch alone; no attending in experiment 2), but not when people were engaged in relatively temporal information processing (duration alone; rhythm alone). Incoherent melodies were judged as shorter than coherent ones when people were attempting to engage in both temporal and nontemporal information processing. This finding was considered an interference effect, where increased in processing load shortened subjective duration; interference effects are robust in the time estimation literature (Brown, 1997), and emerge when attentional resources are taxed and mental workload is high (see Simchy-Gross & Margulis, 2014, 2015). Boltz's findings highlight the complex relationship between musical event structure, information processing, and subjective duration. Incoherent event structures can both lengthen and shorten subjective duration, and it depends on whether people are engaged in relatively temporal or nontemporal information processing.

Event Structure and Information Processing

Music and expectation. Organisms possess great varieties of learned and unlearned expectations—music happens to thrive on their exploitation. Music constantly taunts and teases our sense of knowing what comes next, our involuntary physiological processes that prepare us for future events, our anticipatory responses to things that either confirm, violate, or delay predictions. Expectancy manipulations shape musical experiences—whether listening, imagining, or performing (see Huron, 2006; Huron & Margulis, 2010).

Musical expectancies fall into two broad categories: schematic and veridical (Bharucha, 1987, 1994; Justus & Bharucha, 2001). Schematic expectations are formed by experiencing patterns in the environment over extensive amounts of time, and they inform predictions about general things in broad categories. Schematic expectations always operate automatically, though they can range in depth, and involve relatively conscious and unconscious processing (Margulis, 2005, 2007).

Veridical expectations, on the other hand, are formed by observing patterns in the environment over short periods of time, and they inform predictions about specific things in particular situations. Veridical expectations make unfamiliar music familiar after relatively few exposures. If you hear an unfamiliar song play 12 times on the radio over the course of an hour-long road trip, for instance, that song—and the sequential orderings of its musical events—will be veridically familiar by the time you arrive at your destination.

To illustrate further, consider this: A sequence of letters listed alphabetically is more schematically predictable than that of a sequence of letters listed randomly. The alphabetical list confirms expectations for which we have strong schemas, rooted in years of exposure and rehearsal. Similarly, for an American, the Y symbol is more schematically predictable than the ¥ symbol, because of longstanding exposure.

Now, consider a situation where this American is presented with eight symbols in a row, followed by a ninth symbol. Following a sequence of eight ¥ symbols, a ninth ¥ symbol will be less schematically predictable, yet more *veridically* predictable, than a ninth Y symbol. Schematic expectations continue to favor the occurrence of the ordinary Y, but veridical expectations favor the repetition of the locally established ¥.

Schematic and veridical expectations can, and often do, contradict one another. A good musical example of this comes from the deceptive cadence. Deceptive cadences violate schematic expectations, but can do so while simultaneously confirming veridical expectations. Deceptive cadences violate the schematic expectation that musical passages close on the tonic (a harmony built on the first scale degree). But this violation can occur while simultaneously confirming a well-learned veridical expectation that a particular passage closes on the submediant (a harmony built on the sixth scale degree).

Deceptive cadences violate schematic expectancies about harmonic phrase closure, regardless of veridical predictability. Hearing a song 12 times can make deceptive cadences veridically familiar, for instance, but those familiar deceptive cadences nevertheless remain schematically surprising. Even our favorite songs backed with years of repeated listenings continually surprise us. This type of persistent schematic surprise in the face of veridical familiarity keeps music from getting boring; repetition, in fact, has been shown to make music more engaging, more interesting, more enjoyable, and even more musical (Margulis, 2014; Margulis & Simchy-Gross, 2016).

Chord sequences. A practical and effective way to manipulate musical expectations is to vary the event structure of chord sequences. Chord sequences can be ordered in relatively predictable or unpredictable ways. Predictable chord sequences facilitate temporal information processing, and unpredictable ones facilitate nontemporal information processing. Repeated chord sequences (a single chord presented multiple times), for instance, are predictable—their patterns are easy to abstract. We are accustomed to processing repeated stimuli in daily life—most things usually stay the same (Kruijne & Meeter, 2015). Repeated chord sequences facilitate temporal information processing because they afford listeners plenty of attention to devote to temporal information and track the passage of time. Coherent chord sequences are also relatively predictable. Coherent chord sequences are ordered in ways that confirm well-learned musical expectations and follow the rules of standard tonal harmony. In contrast to both repeated and coherent chord sequences, incoherent chord sequences are relatively unpredictable. Incoherent chord sequences are ordered in ways that violate well-learned musical expectations. Incoherent chord sequences disobey the rules of standard tonal harmony. Incoherent chord sequences facilitate relatively nontemporal information processing. When presented with incoherent chord sequences, people are too occupied trying to make sense of the musical twists, turns, and violations to devote any meaningful amount of attention to temporal information or the monitoring of time.

Although both repeated and coherent sequences are relatively predictable, different processes underlie their perceptions (Huettel, Mack, & McCarthy, 2002). Repetition produces extraordinary perceptual and cognitive effects, enhancing encoding efficiency, predictive attending, and entrainment (Margulis, 2014). Repeated sequences are efficiently processed and easily stored in memory (Saffran, Aslin, & Newport, 1996). Repeated sequences facilitate stimulus identification (Bybee, 2002) and confirm low-level expectations (Dehaene et al., 2001). Repeated stimuli produce robust priming effects (Kristjánsson & Campana, 2010), decreasing task reaction times and errors (Maljkovic & Nakayama, 1994), saccade latencies (McPeek, Maljkovic, & Nakayama, 1999), and the amount of neural activity required for processing (Grill-Spector, Henson, & Martin, 2006; see also Pariyadath & Eagleman, 2012).

Moreover, although both repeated and coherent stimuli facilitate relatively temporal information processing, repeated ones have been shown to do so more effectively than coherent ones. Cai, Eagleman, and Ma (2015) showed that repeated sequences have stronger subjective duration-distorting effects than coherent ones, suggesting that repeated stimuli are perceived more efficiently, capture fewer attentional resources, and facilitate temporal information processing more effectively than coherent stimuli. Repeated stimuli have also been shown to facilitate priming effects to a greater degree than similar, yet not identical, stimuli (Koutstaal et al., 2001).

In contrast to repeated chord sequences, coherent ones recruit a great number and variety of musical expectations. Most of the music we hear in daily life is structurally coherent. It is rare that we hear a song on the radio repeat the first musical event innumerably. Although repetition is a core musical element (Margulis, 2014), the kind of repetition that characterizes music is not generally the ceaseless repetition of a single event. Nonetheless, in the present research, we will refer to single repeating elements (e.g., I—I—I—I—I—I) as repeated chord sequences, and collections of different, yet organized, elements as coherent chord sequences (e.g., iii—vi—ii—IV—V—vii°—I).

Different, yet organized, musical elements—those ordered in structurally coherent ways—are frequently encountered in everyday life. People of western society most often hear structurally coherent music, and thus form strong schemas that music, in general, should sound coherent. These schemas, or schematic expectations, govern our perceptions of music. The ability that music has to form, confirm, violate, and delay expectations is a big part of what makes music emotionally moving and engaging. How does music manage to pull us to the edge of our seats at a concert hall, or make us jump up and down at a festival? Music does this by diligently manipulating, teasing, twisting, and turning our sense of knowing what we are going to hear, and when we are going to hear it.

Manipulations of musical expectations, furthermore, facilitate both temporal and nontemporal information processing. We expect musical chord sequences to both contain typical chords, such as dominants and tonics. This is an expectation about nontemporal information. We also expect the tonic to *follow* the dominant—an expectation about temporal information. Coherent chord sequences confirm both of these types of expectations—expectations about both temporal and nontemporal information. Coherent chord sequences include both the "usual suspects" and their "usual orderings." Thus, coherent chord sequences, having both predictable temporal and nontemporal elements, facilitate both temporal and nontemporal information processing.

In sum, repeated chord sequences facilitate temporal information processing, and coherent chord sequences facilitate both temporal and nontemporal information processing. The distinction between the type of temporal information processing facilitated by repeated and coherent chord sequences is that coherent ones facilitate temporal information processing by focusing attention on temporal musical properties (e.g., rhythm), whereas repeated chord sequences facilitate temporal information processing by allowing attention to effectively track the passage of time (e.g., count seconds). It is easier to count seconds when presented with repeated events than when presented with non-repeated events because repeated events capture relatively few attentional resources and consume relatively little cognitive capacity (Boltz, 1995; Jones & Boltz 1989; Zakay, 1993; Zakay & Block, 1995).

Music and Time

Music is particularly well suited for the study of psychological time. There are many reasons for this, 10 of which are outlined here: (1) music is temporal, (2) music is an auditory stimulus, (3) music comprises pitches, (4) music comprises chords, (5) music is highly structured, (6) music lacks a semantics, (7) music manipulates expectations, (8) music affects emotions, (9) music distorts subjective time, and (10) music is pervasive in the literature.

Music is temporal. Time is intrinsic to music. Music consists of events that change over time. Pitches go up and down. Harmonies modulate. Rhythms are temporal patterns established by the rate of these changes. In contrast to static art forms, such as paintings and sculptures, music changes over time—music is dynamic. Temporal relationships between chord sequences play a key role in the processing of musical harmony (Bigand, Madurell, Tillmann, & Pineau, 1999). The different ways in which music unfolds over time uniquely affect subjective experiences of time.

Music is an auditory stimulus. The auditory modality has extremely high temporal resolution (Block, 1990). People have better temporal sensitivity in the auditory than in the visual modality (Shams & Kim, 2010; Ortega, Guzman-Martinez, Grabowecky, & Suzuki, 2014), and are better at discriminating temporal intervals with the help of auditory cues than visual cues (Grondin & McAuley, 2009). Auditory information, moreover, has been shown to affect visual duration judgments, but not vice versa (Klink, Montijn, & van Wezel, 2011). Human perceptions of temporal phenomena are most often studied in the auditory domain (Penhune, Zatorre, & Evans, 1998).

Music comprises pitches. Pitch stimuli have better temporal sensitivity than speech stimuli (Grondin, Bisson, & Gagnon, 2011). Pitches have their own memory store (Deutsch, 1972), making memory for pitches resilient to speech masking (Deutsch, 1970). Pitch stimuli afford more experimental control than speech stimuli—speech is one of most complex auditory signals in the environment (Donnadieu, 2007).

Pitch stimuli are often preferred to speech stimuli when conducting time estimation research (Field & Groeger, 2004; Ponsot, Susini, & Meunier, 2015; Sasaki et al., 2010). Sequences of pitches (melodies) are informative (see Boltz, 1989, 1991, 1992a, 1993, 1998; Boltz & Jones, 1986), and sequences of *overlapping* pitches (chord sequences) are especially informative (see Bigand & Parncutt, 1999; Bigand et al., 1999; Bigand, Poulin, Tillmann, Madurell, & D'Adamo, 2003; Bueno & Ramos, 2007; Droit-Volet, Bigand, Ramos, & Bueno, 2010; Firmino & Bueno, 2008, 2013, 2014; Firmino, Bueno, & Bigand, 2009; Lebrun-Guillaud & Tillmann, 2007; Lebrun-Guillaud, Tillmann, & Justus, 2008; Regnault, Bigand, & Besson, 2001; Schmuckler & Boltz, 1994; Tillmann & Bigand, 2001; Tillmann, Bigand, & Pineau, 1998; Tillmann & Lebrun-Guillaud, 2006).

Music comprises chords. When the empirical goal is to produce strong manipulations of expectation, chord sequences are often superior to pitch sequences. Chord sequences manipulate expectations about a greater number of musical events than pitches, expectations about harmonic—in addition to melodic—relationships between musical events, and expectations about the manner in which those harmonic musical events change within sequences. Whereas pitches manipulate expectations about individual tones, chord sequences manipulate expectations about groups of overlapping tones. Whereas pitches manipulate melodic expectations, chords manipulate both melodic and harmonic expectations. Whereas melodies confirm, violate, and delay predictions about the behavior of melodic intervals, chord sequences confirm, violate, and delay predictions about the behavior of both melodic and harmonic intervals, which triggers musical expectations that are involuntary and firmly engrained in the human cognitive system from extended exposure to western tonal music. Moreover, in contrast to melodies, chord sequences manipulate expectations about voice leading, or the ways in which individual pitches within each chord move between subsequent chords.

Music is highly structured. Event structure is a key factor in time estimation research, and music has rich varieties of well-understood event structures. Very specific rules dictate the relationships between musical elements (Lerdahl & Jackendoff, 1983). The high degree of structure in music makes it easy to manipulate structural coherence and shift temporal orientation.

Music lacks a semantics. Musical syntactic processing involves the same brain areas as linguistic syntactic processing (Patel, 2003, 2007). Both language and music activate robust and well-researched sets of expectations. Just as linguistic syntactical and grammatical rules are reinforced by linguistic expectancies, musical well-formedness rules are reinforced by musical expectancies. Just as people have strong expectations for how speech unfolds, people have strong expectancies for how music unfolds. Indeed, violations of musical well-formedness rules activate similar neural networks as violations of linguistic syntactical and grammatical rules (Maess, Koelsch, Gunter, & Friederici, 2001).

That said, music and language are distinct in how they transmit meaning. Meaning in language depends on semantic comprehension; meaning in music, on the other hand, revolves around the manipulation of expectation. Language has semantic meaning; music has aesthetic meaning. In this way, music affords the opportunity to enhance experimental control. Since music lacks a clear semantics, it eliminates a potential complicating factor in stimuli design.

Music manipulates expectations. Expectation is an undeniably important factor in time estimation research. Gaudreault and Fortin (2013), Thomaschke, Kiesel, and Hoffmann (2011), and Boltz (1998) have all shown that expectancy manipulations affect people's subjective experiences of time. Few mediums manipulate expectations more naturally and to a greater extent than music.

Music affects emotions. Music impacts emotions (Juslin & Västfjäll, 2008; Meyer, 1956) and emotions impact psychological time (Wittmann & Paulus, 2008). The manipulation of musical expectancies is one of the most central ways that music shapes emotional experiences. Musical surprise registers as tension, and as expectations develop and are thwarted and satisfied, dynamic patterns of perceived tension and resolution emerge.

Music affects subjective time. Music is dynamic, and its progression shapes durational experiences. Music can shorten subjective duration, making time seem to have passed relatively quickly—we often lose track of time while listening. Listening to our favorite tunes might make time seem to "fly by" by turning our focus away from the passage of time. Music can also lengthen subjective duration, making time seem to have passed relatively slowly. We sometimes find ourselves focusing on nothing but time when hearing undesirable music. Unwanted party music might make failed attempts to sleep seem to last forever.

Music is pervasive in the literature. Researchers often use music to study psychological time (see Bailey & Areni, 2006; Barnes & Jones, 2000; Bigand et al., 1999; Bisson, Tobin, & Grondin, 2009; Boltz, 1989, 1991, 1992a, 1992b, 1993, 1994, 1995, 1998; Bueno, Firmino, & Engelmann, 2002; Chebat, Gelinas-Chebat, & Filiatrault, 1993; Jones, 1990; Jones, Boltz, & Kidd, 1982; Kellaris & Kent, 1992; Phillips & Cross, 2011; Ziv & Omer, 2010). Some models of time estimation, in fact, revolve almost entirely around music (see Jones & Boltz, 1989; Schafer, Fachner, & Smukalla, 2013; see also Caetano, Mouchtaris, & Wiering, 2012). This existing body of research makes it easy to frame new studies about music and psychological time.

Time Estimation Method

Verbal estimation. One of the most common methods to measure subjective duration is verbal estimation (Bisson, Tobin, & Grondin, 2009). Verbal estimates are explicit reports of subjective duration made using numeric labels (e.g., seconds). It is particularly appropriate to use the method of verbal estimation when measuring the subjective duration of relatively long intervals. Verbal estimates are practical because they help keep experiments to reasonable lengths—people can report numeric values relatively quickly. Using the method of verbal estimation can be troublesome, however, because verbal estimates rely on language. People making verbal estimations are burdened with the tricky task of translating subjective temporal experiences into objective temporal labels.

Duration reproduction. The method of duration reproduction does not rely on language. Duration reproductions involve remembering, imagining, and replicating previously experienced temporal intervals. Duration reproductions can be produced after participants experience a temporal interval by either (a) experimentally marking the beginning of a reproduction interval and instructing people to press a button after an identical amount of time as the experienced interval has passed, (b) instructing people to press a button to both start and stop a timer to demarcate a duration identical to the experienced interval, or (c) instructing people to hold down a button for a duration identical to the experienced interval. Most common is the version that requires people to both start and stop a timer, probably because it yields the most accurate estimates (Mioni, Stablum, McClintock, & Grondin, 2014).

The method of duration reproduction is arguably the most reliable and sensitive measure of subjective duration (Fraisse, 1963; McKay, 1977). The method of duration reproduction is best suited for relatively short intervals—people tend to underestimate duration as the actual durations of intervals lengthen.[1] That said, it is ideal to use more than one method of measuring subjective duration when conducting time estimation research (Brown, 1985). Researchers tend to use both verbal estimation and duration reproduction in the same experiment (Block, George, & Reed, 1980; Brown, 1985; Warm, Smith, & Caldwell, 1967).

Musical imagery reproduction. Explicit short interval time estimation experiments use methods of measuring subjective duration such as verbal estimation and duration reproduction (Grondin, 2010). The instructions in these types of experiments, however, include the word "duration" or "time."[2] No short interval time estimation experiments have included instructions that do *not* state duration.[3]

In contrast to typical explicit short interval time estimation experiments, we used a novel type of reproduction to measure subjective duration that avoids stating duration or time in the experimental instructions. We instructed people to generate musical imagery, recorded the amount of time it took people to do so, and treated those emergent temporal intervals as measures of subjective duration.[4] We term these emergent temporal intervals musical imagery reproductions. There is evidence to suggest that musical imagery reproductions can be treated as, and are sensible and accurate representations of, subjective duration.

Halpern and Zatorre (1999), investigating the neurological correlates of musical imagery using melodies, instructed people to listen to musical clips, imagine them, and then press a button when the clips reached their original ending points. To confirm that the auditory images were conforming to the actual durations of the musical clips, they compared the differences between the latencies of the short, medium, and long trials. The amount of time that passed from the offsets of the musical clips to the final button presses matched the actual durations of the clips. These findings show that musical imaginings can yield relatively accurate measures of subjective duration, without requiring participants to undertake an explicitly temporal task—without stating duration or time in the experimental instructions.

Grondin and Killeen (2009), furthermore, instructed people to make duration reproductions while either singing familiar songs, counting seconds, or refraining from engaging in time-keeping behaviors. Duration reproductions created while singing were as accurate as those created while counting. These findings suggest that timing mechanisms involved in singing are similar to those involved in duration estimation. Moreover, Weber and Brown (1986) showed that it takes the same amount of time to imagine musical clips as it does to sing them. And people tend to imagine songs at their original tempos (Levitin & Cook, 1996; see also Halpern, 1988b).

Musical imagery reproductions are similar to duration reproductions. Both require starting and stopping timers while mentally rehearsing information stored in memory, and both likely involve similar temporal representations (see Halpern, 1988a); even visual imagery has emergent temporal properties (Kosslyn, Ball, & Reiser, 1978).[5] The distinction between musical imagery reproductions and duration reproductions is that the instructions of duration reproductions explicitly state duration, whereas those of musical imagery reproductions do not.

Duration reproductions involve retrieving from memory and rehearsing temporal information. Musical imagery reproductions, on the other hand, involve retrieving from memory and rehearsing *musical* information (Halpern & Zatorre, 1999). Musical information comprises both temporal and nontemporal properties.[6] Hence, people imagine and rehearse more nontemporal information—and engage in more nontemporal information processing—when making musical imagery reproductions than when making duration reproductions. Musical imagery reproductions facilitate nontemporal information processing.

People also engage in more nontemporal information processing when making musical imagery reproductions than when making verbal estimations. Verbal estimations only involve retrieving from memory and reporting temporal information—only involve attending to the passage of time and stating a numeric label. Verbal estimations facilitate temporal information processing.

Time Estimation Paradigm

Subjective duration can be measured in one of two paradigms: prospective or retrospective. In prospective paradigms, participants know that duration judgments will be asked of them prior to the start of trials; in retrospective paradigms, participants do not. In retrospective paradigms, participants are asked to make duration judgments only *after* the experimental trial has ended. Prospective duration judgments illuminate how factors affect psychological time when people focus on the passage of time during the to-be-judged interval. Retrospective duration judgments, on the other hand, illuminate how factors affect psychological time when people focus on things *unrelated* to the passage of time during the to-be-judged interval.

Some researchers have considered prospective judgments to be measures of experienced duration, and retrospective ones to be measures of remembered duration (Block, 1974, 1990; Zakay & Block, 2004). Yet because both types of duration judgments are collected *following* the experienced interval, and thus rely on memory (Rattat & Droit-Volet, 2010), it seems appropriate to consider prospective judgments as those that rely on remembered temporal information, and retrospective ones as those that rely on remembered *nontemporal* information.

Prospective judgments tend to be more accurate, less variable, and longer than retrospective ones (cf. Grondin & Laflamme, 2015). Both prospective and retrospective judgments are likely driven by distinct cognitive (Zakay & Block, 2004) and neurological processes (Rao, Mayer, & Harrington, 2001), but might nevertheless involve similar timing mechanisms (Block, 1992; Brown & Stubbs, 1988).

Researchers using the retrospective paradigm face methodological limitations: Retrospective duration judgments are often unclear, unreliable, and inconsistent (Block et al., 1980; Hicks, Miller, & Kinsbourne, 1976; Zakay, 1989). Retrospective duration judgments are hard to interpret, and represent time estimation processes that are hard to manipulate. Furthermore, a retrospective experiment reveals its true purpose to participants only after its completion.

Researchers have devised elaborate measures to prevent people from suspecting the importance of the passage of time in retrospective experiments. Zakay (1993), for instance, refrained from asking people to remove their watches because this question might have shifted attention to the passage of time. Instead, Zakay required that people use their non-dominant hands to complete the experimental tactual tracing tasks, keeping the hand most likely to bear a watch under the table, and preventing them from glancing at it during the experiment.

Only the first experimental trial can be retrospective—all trials thereafter are contaminated by the awareness of upcoming duration judgments. Some researchers have found ways around this limitation. For instance, Jones and Boltz (1989) had participants memorize all of the melody stimuli in the first experimental block, and then estimate the durations of all of the melodies in the second experimental block.

Although there are ways to work around the limitations associated with the retrospective paradigm, there are more practical and less problematic ways for researchers who aim to facilitate nontemporal information processing to do so than using the retrospective paradigm. Researchers might find it useful to use musical imagery reproductions, for instance. Musical imagery reproductions both facilitate nontemporal information processing and, among other things, allow participants to complete multiple trials while staying ignorant to the true purpose of the experiment.

Time Estimation Models

Dynamic attending theory. Jones and Boltz (1989) emphasize that event structure plays an important role in psychological time. The extent to which temporal and nontemporal information are structurally compatible influences the degree to which people attend to relatively low-level stimulus characteristics (analytic attending) or high-level ones (future-oriented attending). Moreover, incompatible (incoherent) event structures can disorient listeners, consume attentional resources, disrupt memory, and distort duration estimates. Confirmed, violated, and delayed expectations can make incoherent event structures that seem to end too early seem relatively short, and ones that seem to end too late seem relatively long. The importance of factors such as event structure, dynamic attending, and expectations in time estimation research cannot be overstated (Phillips, 2015).

Attention-based models. Attention-based models of short interval time estimation argue that the riddle of subjective duration can be solved simply by considering whether people focus on time, or not. The more we focus on time, the longer time should seem to last; the less we focus on time, the shorter time should seem to last.

Attention-based models emphasize that people have both a temporal processor and a nontemporal processor. These processors compete for limited attentional resources (Kahneman, 1973). The more attentional resources allocated to the temporal processor, the longer duration estimates should become; the more attentional resources allocated to the nontemporal processor, the shorter duration estimates should become (Thomas & Brown, 1974; Thomas & Weaver, 1975).

The attentional gate model, for instance, theorizes that subjective temporal units, or pulses created by a pacemaker, pass through a cognitive “gate” and accumulate in a cognitive “counter” (Zakay & Block, 1995). The more attentional resources that are allocated to time during an interval, the wider the gate opens, the more pulses are counted, and the longer subjective duration estimates should become.

Memory-based models. Memory-based models posit that subjective duration is a function of the amount of meaningful information stored in and retrieved from memory. The storage size hypothesis, for example, theorizes that the greater the amount of information stored in memory, the longer duration estimates should become (Ornstein, 1969). Similarly, the contextual change (Block, 1978, 1982, 1989, 1990; Block & Reed, 1978) and change segmentation (Poynter, 1983, 1989; Poynter & Homa, 1983) hypotheses state that the greater the amount of contextual changes and high priority, or attention-capturing, events perceived and stored in memory, the longer duration estimates should become. The more meaningful chunks of information we remember in retrospect (Friedman, 1993), the longer things should seem to have lasted.

Competing models. Attention- and memory-based models make different predictions about how various factors will affect subjective duration. One factor that these models make opposite predictions about is nontemporal information processing load, or nontemporal task difficulty. Nontemporal task difficulty, mental workload, or nontemporal information processing load refers to the amount of effort, cognitive resources, cognitive capacity, or information processing load required to complete a nontemporal task (Brown & Boltz, 2002; Proctor, Lu, Van Zandt, & Weeks, 1994). For example, the nontemporal task difficulty of the Color-Word Stroop task (Stroop, 1935) is greater than that of the Word Stroop task (Logan, 1980; Logan & Zbrodoff, 1979). The simultaneous presentation of colors and words in the Color-Word Stroop task consumes relatively many attentional resources, thereby eliciting greater reaction times and numbers of errors (Dyer, 1973).

Attention-based models predict that greater nontemporal task difficulty will shorten subjective duration. This is because greater nontemporal task difficulty should serve to distract attention from the passage of time, decreasing the number of accumulated subjective temporal units counted at the time of judgment, and thus shortening duration estimates. Memory-based models, in contrast, predict that greater nontemporal task difficulty will lengthen subjective duration because greater nontemporal task difficulty should serve to increase the amount of high priority events perceived during the interval and remembered at the time of judgment, thus lengthening duration estimates.

A unified model. The resource allocation model (RAM) asserts that the ways in which nontemporal task difficulty affects subjective duration are contingent upon the degree to which people are engaged in relatively temporal or nontemporal information processing. Nontemporal task difficulty should shorten subjective duration when people are engaged in relatively temporal information processing, but *lengthen* subjective duration when people are engaged in relatively nontemporal information processing.

According to the RAM, there exists a temporal processor, or an attentional timer (Berlyne, 1966), that stores and counts subjective temporal units (e.g., seconds), and a nontemporal processor, or a memory-based mechanism, that stores and counts high-priority events and contextual changes (e.g., textures). Both processors encode the contents of intervals. People can attend to the contents of intervals while engaging both processors. The amount of attentional resources allocated to each processor varies. The degree to which people engage a particular processor determines that processor's contribution to the duration estimates. The more that people attend to and remember information encoded in a processor, the more that processor will contribute to duration estimates.

Relatively high amounts of attentional resources are allocated to, and traces of information are retrievable from, the temporal processor when, for example, people judge duration prospectively, or when people are presented with homogeneous, or repeated, stimuli (Zakay, 1993). In contrast, relatively high amounts of attention are allocated to, and traces of information are retrievable from, the nontemporal processor when people judge duration retrospectively, or when people are presented with unpredictable, or incoherent, stimuli (Jones & Boltz, 1989; Zakay & Block, 1995).

The RAM was motivated by the observation that although attention- and memory-based models make contradictory predictions, both models are valid in certain contexts. Findings explained by attention-based models tend to emerge in conditions where people are aware of upcoming duration judgments, estimate duration immediately after intervals end, and base duration estimates on temporal information stored in short-term memory. These conditions facilitate temporal information processing. On the other hand, findings explained by memory-based models tend to emerge in conditions where people are ignorant to upcoming duration judgments, estimate durations after delays when intervals end, and base duration estimates on nontemporal information stored in long-term memory.[7] These conditions facilitate nontemporal information processing.

Neither attention- nor memory-based models can solely account for all of the contradictory results found in time estimation studies testing the effects of time estimation paradigm, but together they can: Attention-based models tend to explain duration estimates in prospective paradigms; memory-based models tend to explain duration estimates in retrospective paradigms (Block & Zakay, 1997). Similar conclusions can be drawn in studies testing the effects of time estimation delay and time estimation reference (Zakay, 1989, 1993; Zakay & Fallach, 1984).[8]

Evidence for the RAM. Miller, G. W., Hicks, and Willette (1978) showed that greater nontemporal task difficulty (fewer rehearsed trials) shortened subjective duration when people were engaged in relatively temporal information processing (rehearsal; prospective), but lengthened subjective duration when people were engaged in relatively nontemporal information processing (rehearsal; retrospective).

Block et al. (1980) varied whether or not a liquid beaker boiled and instructed participants to “observe the beaker.” Intervals that contained boiling liquid were judged as shorter than those that did not when people were engaged in relatively temporal information processing (reproductions; prospective), but as longer than those that did not when people were engaged in relatively nontemporal information processing (reproductions; retrospective).

McClain (1983) manipulated nontemporal task difficulty by varying the length of word lists. She required that participants classify words based on either shallow, graphemic properties or deep, semantic ones. Greater nontemporal task difficulty (longer lists) shortened subjective duration when people were engaged in relatively temporal information processing (prospective; semantic-intentional; semantic-incidental), but lengthened subjective duration when people were engaged in relatively nontemporal information processing (retrospective).

Zakay and Fallach (1984) showed that greater nontemporal task difficulty (high-difficulty Stroop task) shortened subjective duration when people were engaged in relatively temporal information processing (immediate estimation), but not when people were engaged in relatively nontemporal information processing (remote estimation).

Zakay (1989) similarly showed that greater nontemporal task difficulty (CW Stroop task) shortened subjective duration when people were engaged in relatively temporal information processing (prospective-immediate estimation), but not when people were engaged in relatively nontemporal information processing (prospective-remote estimation).

Zakay (1993), in addition, showed how factors that manipulate information processing can interact. Zakay found that greater nontemporal task difficulty (complex tactile shapes) shortened subjective duration when people were engaged in relatively temporal information processing (absolute; prospective), but lengthened subjective duration when people were engaged in relatively nontemporal information processing (relative; retrospective).

Zakay, Tsal, Moses, and Shahar (1994) varied the degree to which stimulus properties promoted interval segmentation—participants perceived auditory word and tactual letter lists as having greater or fewer numbers of "chunks." Greater segmentation lengthened subjective duration when people were engaged in relatively nontemporal information processing (retrospective-absolute; retrospective-comparative), but did not affect subjective duration when people were engaged in relatively temporal information processing (prospective-absolute; prospective-comparative).[9]

Zakay and Block (2004) manipulated nontemporal task difficulty in a variety of ways, showing how varying levels of syntactic ambiguity, Stroop task difficulty, and task switching can compound to increase difficulty.[10] Greater nontemporal task difficulty shortened subjective duration when people were engaged in relatively temporal information processing (prospective), but lengthened subjective duration when people were engaged in relatively nontemporal information processing (retrospective).

As a whole, these studies lend a good deal of evidence in support of the RAM. The RAM unifies the predictions of both the attention- and memory-based models of time estimation, maximizing its predictive power, accuracy, and specificity. The RAM provides a useful framework from which to make predictions about the effects of attention-capturing stimuli on psychological time.

Temporal expansion hypothesis. In 2004, Tse, Intriligator, Rivest, and Cavanagh ran a series of experiments showing how oddballs are judged as longer than standards.[11] The finding that oddballs are judged as longer than standards is robust and reliable in the time perception literature, and is known as the temporal oddball effect, or the temporal oddball illusion (Birngruber, Schröter, & Ulrich, 2014a, 2014b, 2015a; Kim & McAuley, 2013; Pariyadath & Eagleman, 2007, 2012; Schindel, Rowlands, & Arnold, 2011; see also Birngruber, Schröter, & Ulrich, 2015b; Matthews, 2015; Matthews & Gheorghiu, 2016).

Tse et al. (2004) proposed the temporal expansion hypothesis to explain why oddballs are judged as longer than standards: Oddballs expand, or lengthen, subjective duration because oddballs capture attention, increase the rate of information processing, and increase the number of subjective temporal units stored and counted in a cognitive timer. Tse et al. based this hypothesis on the tenets of attention-based models of short interval time estimation, such that attention-based models assert the existence of a counter mechanism that accumulates and tallies the number of subjective temporal units registered in a cognitive timer (Thomas & Weaver, 1975; Treisman, 1963). Attention-capturing stimuli should shorten subjective duration because when stimuli capture attention, more attentional resources are directed to the nontemporal information of the stimuli, and fewer attentional resources are directed to time-keeping behaviors.

Rationale for the Present Research

Past research shows that oddballs are judged as longer than standards, but no research has tested whether or not this temporal oddball illusion applies to intervals, in addition to individual events. Are intervals that contain oddballs judged as longer than those that do not? The temporal expansion hypothesis predicts that people will judge intervals that contain oddballs as longer than those that do not. The RAM, on the other hand, predicts that people will judge intervals that contain oddballs as shorter than those that do not when people are engaged in relatively temporal information processing, but as longer than those that do not when people are engaged in relatively nontemporal information processing.

The temporal expansion hypothesis asserts that oddballs lengthen subjective duration because more subjective temporal units are stored and counted in the cognitive timer when perceiving oddballs than when perceiving standards. If this is true, then more subjective temporal units should be stored and counted in the cognitive timer when perceiving intervals that contain oddballs than when perceiving otherwise identical intervals that do not contain oddballs. Therefore, if the temporal expansion hypothesis is valid in the context of intervals, in addition to individual events, in addition to the context of individual event time perception, then we should find that intervals that contain oddballs are consistently judged as longer than those that do not.

The RAM, in contrast, posits that the inclusion of oddballs in intervals should both distract attention from the passage of time when people are engaging in relatively temporal information processing and increase the number of high-priority events perceived and remembered when people are engaging in relatively nontemporal information processing. Therefore, if the RAM is valid, then we should find that intervals that contain oddballs are judged as shorter than those that do not when people are engaged in relatively temporal information processing, but as longer than those that do not when people are engaged in relatively nontemporal information processing.

The present research tests these competing hypotheses. In two experiments, we manipulated whether or not musical chord sequences contained oddballs, and the degree to which people were engaged in relatively temporal or nontemporal information processing.

Experiment 1

In experiment 1, we manipulated the degree to which people were engaged in relatively temporal or nontemporal information processing by (a) instructing participants to make either verbal estimations or musical imagery reproductions (response type), and (b) varying whether chord sequences were repeated, coherent, or incoherent (event structure).

We were inspired to vary response type by other studies showing that varying the types of judgments people make is an effective way to manipulate the degree to which people engage in relatively temporal or nontemporal information processing (Zakay, 1993; Zakay et al., 1994). Much of the previous research, however, has used the retrospective paradigm to facilitate nontemporal information processing. We used the novel and covert method of musical imagery reproduction to facilitate nontemporal information processing. Musical imagery reproductions allowed us to facilitate nontemporal information processing while avoiding some of the methodological issues associated with the retrospective paradigm.

We chose to vary musical event structure because it is particularly well suited to manipulate the extent to which people engage in relatively temporal or nontemporal information processing (Boltz, 1992b, 1995, 1998, 1999; Brown & Boltz, 2002; Jones, 1990; Zakay, 1993), but is seldom used to do so. We used chord, rather than pitch, sequences to manipulate a greater number and variety of expectations (e.g., harmony and voice leading). Repeated chord sequences are highly predictable, consume relatively few attentional resources, and facilitate temporal information processing—people presented with repeated events are able to allocate most of their attentional resources to time-keeping. In contrast, incoherent chord sequences are unpredictable, consume relatively many attentional resources, and facilitate nontemporal information processing—expectancy violations consume attentional resources that would have otherwise been available to track time. Coherent chord sequences are relatively predictable, confirm schematic and veridical musical expectancies, draw attention to both temporal and nontemporal musical properties, and facilitate both temporal and nontemporal information processing.

Method

Participants. A total of 56 undergraduate students enrolled in General Psychology at the University of Arkansas volunteered to participate in this experiment in exchange for course credit. We excluded from the analysis the data of 4 participants (2 reported abnormal hearing, 1 experienced technical issues, and 1 disregarded instructions). The remaining 52 participants (31 females) ranged from 18 to 39 years of age (*M* = 19.88; *SD* = 3.45). None were music majors, but 9 had received formal musical training for at least 1 year, ranging from 1 to 8 years (*M* = 3.60; *SD* = 2.61). All of the participants gave informed consent before participating in this experiment. This experiment was approved by the University of Arkansas IRB.

Stimuli. We composed novel chord sequences using Finale 2012 music notation software. We created original chord sequences to control for extraneous variables and prior familiarity, isolating the musical variables of interest and ruling out the possibility that participants have previously heard the music. The chord sequences were composed of 4-voice (SATB) piano chords (no rests or silences)—half contained oddballs, half did not. The oddball was a sliding tone (E2 to F#6; 82 Hz to 1480 Hz; following Tse et al., 2004) played with an Ocarina timbre.[12] We normalized the amplitude of the chord sequences using Audacity (2.0.6).

The first chord of all of the chord sequences was root position C Major. This chord played consecutively in the repeated chord sequences (see Figure 1). The coherent and incoherent chord sequences included chords taken from the scale of C Major (I, ii, iii, IV, V, vi, vii°; i.e., C Major, D Minor, E Minor, F Major, G Major, A Minor, B Diminished). The distinction between the coherent and incoherent chord sequences was the order of the chords, not the chords themselves. We ordered the chords in the coherent chord sequences in ways that conformed to the rules of standard tonal harmony, such as voice leading, harmonic change, and melodic resolution (see Figure 2). In contrast, we ordered the chords in the incoherent chord sequences in ways that violated those rules (see Figure 3).

The incoherent chord sequences were merely scrambled versions of the coherent ones. Kowal (1987) made coherent musical tone sequences incoherent by reversing the order of the tones. Kowal violated veridical, in addition to schematic, musical expectancies—the tone sequences were taken from familiar traditional folk tunes. We aimed to control for prior exposure and familiarity in experiment 1. We scrambled the coherent chord sequences (e.g., iii—vi—ii—IV—V—vii^{o}—I) to create corresponding incoherent versions (vi—V—ii—I—vii^{o}—IV—iii) similar to how Pariyadath and Eagleman (2007) scrambled predictable number sequences (1—2—3—4—5) to create corresponding unpredictable versions (e.g., 1—4—3—5—2).

In the chord sequences that contained oddballs, an oddball occurred once after every two to six chords, and one of those oddballs always occurred on the final beat of the chord sequence. The chord sequences that contained oddballs were in all other regards identical to those that did not (see Figure 4).

We varied whether the chord sequences were repeated, coherent, or incoherent (three levels), and whether or not they contained oddballs (two levels) independently. This created six possible oddball X event structure pairings. To broaden generalizability, we created 12 "base" chord progressions (each of which had six oddball X event structure pairing versions). This produced 72 unique chord sequences. We then created 12 variations (crossed in a between-subjects Latin-square design) of each of the 72 unique chord sequences. These 12 variations differed in oddball placement set, or the particular sequential positions where the oddballs occurred—we placed oddballs on different musical beats. All other factors were held constant.

To create the 12 "base" chord progressions, we varied the actual duration, the tempo, and rhythm of the chord sequences independently. We used three different durations, two different tempi, and two different rhythms—this produced 12 duration X tempo X rhythm pairings. The three durations were 3.5 s, 7 s, and 12 s. The two tempi were 71 beats per minute (bpm; 850 ms IOI) and 86 bpm (700 ms IOI). For the two rhythms, where eighth notes occurred in rhythm I, triplets occurred in rhythm II, and vice versa; both rhythms were composed of quarter notes (one chord per beat), eighth notes (two chords per beat), and triplets (three chords per beat). The 12 base chord progressions were identical in all other regards. We varied tempo and rhythm to discourage identical trial responses, and encourage thoughtful and active participation. We varied duration to help account for methodological inconsistencies in the literature. It is important to use a variety of durations in every time estimation experiment because researchers often find different results when studying stimuli of different durations (Brown, 1985). Moreover, we included durations both shorter and longer than 5 seconds to expand generalizability to durations that rely on relatively short- and long-term memory, and to durations within the perceptual present, or specious present (see Block, 1990; Clark, 1999; Fraisse, 1984; James, 1890).

Each participant heard each of the 72 unique chord sequences twice, amounting to 622 chords and 74 oddballs, over the course of the experiment. The overall probability, then, of an oddball occurring was 11 %, comparable to other influential investigations of the effects of oddballs on subjective duration (see Tse et al., 2004).

Procedure. The experiment took place in a quiet room in the Music Cognition Lab at the University of Arkansas. Participants were tested individually in a 4’ x 4’ WhisperRoom sound isolation enclosure (MDL 4848E/ENV). They sat facing a 22” Dell P2212H monitor while wearing Sennheisser HD 600 open-air, around-ear headphones, and made responses using the computer keyboard, mouse, and DirectIN Rotary Controller (PCB v2014). The auditory stimuli were presented binaurally at a comfortable listening level. The experiment was presented using DirectRT (Version 2014; Empirisoft Corporation, New York, NY) on a Dell OptiPlex 7010 desktop computer running Windows 7. Participants signed the consent form and placed all of their belongings and potentially distracting materials (e.g., phones and watches) in the experimental waiting room before entering the booth. Participants progressed through the experiment at their own pace.

The experiment consisted of two blocks. Each block consisted of three practice trials, followed by 72 randomly presented experimental trials. Each participant completed 144 experimental trials over the course of the experiment. In each of the trials, participants pressed a button to start a chord sequence and, after its completion, made a response. This response was a musical imagery reproduction in the first block, and a verbal estimation in the second block.

In the first block, immediately upon the closure of the chord sequence in each trial, participants were presented with the on-screen question: “What is the duration of this excerpt? In other words, how many seconds passed from the moment it started to the moment it finished?” Participants were encouraged to round to the 10th decimal place and be as specific and accurate as possible.

In the second block, immediately upon the closure of the chord sequence in each trial, participants were presented with the on-screen instructions: “Imagine that excerpt playing back in your head. Re-play it through your head the exact way you heard it play through the headphones—from start to finish. Actually imagine it sound in your head exactly as you heard it sound through the headphones. Press the green button to mark the start of the excerpt you're imagining. Press the red button to mark the finish of the excerpt you're imagining."

A brief demographic questionnaire concluded the experiment, which lasted about 50 min.

Data Analysis. We analyzed these data using linear mixed modeling (LMM; see Baayen, 2008; Quené & Van den Bergh, 2004; Finch, Bolin, & Kelley, 2014). The four within-subjects fixed-effects factors were oddball (yes or no), response type (verbal estimation or musical imagery reproduction), event structure (repeated, coherent, or incoherent), and actual duration (3.5 s, 7 s, or 12 s). The between-subjects fixed-effect was oddball placement variation (12 levels). The covariate was formal musical training (had or had not received training for at least 1 year; following Janata & Paroo, 2006). The random effects were subject (52 levels) and item (base chord progression; 12 levels). We obtained a standardized measure of subjective duration by dividing the raw verbal estimation and musical imagery reproduction responses (ms) by the actual durations of the chord sequences. Ratio scores represent directional bias; values above 1 represent overestimations and values below 1 represent underestimations (see Hornstein & Rotter, 1969). The data consisted of 7488 normally distributed ratio scores, 31 of which were identified as outliers using the generalized extreme studentized deviate method, and excluded from the analysis (Rosner, 1983).

We first ran the maximal model that included all of the factors and their interactions, and the random slopes of each of the factors within each of the subject and item crossed grouping variables. We included maximal random slopes of the fixed effects to account for random slope variance, and omitted the random slopes of the fixed effects in order of least random variance to obtain model convergence (following Barr, 2013; Barr, Levy, Scheepers, & Tily, 2013). The final converged model included the random slopes of oddball and response type with the subject grouping variable, and the random slopes of event structure and response type with the item grouping variable.

Pseudo-R^2 was .353, indicating that the final model explained, or modeled, 35.3 % more variance than the base model (the base model included only the subject and item grouping variables; Snijders & Bosker, 1994). The intercorrelation coefficients for subjects and items were .295 and .06, respectively, displaying substantial clustering among subjects and mild clustering among items.

We ran the analysis in R (R Core Team, 2015) with restricted maximum likelihood using the *lmer* function of the *lme4* package (Bates, Maechler, Bolker, & Walker, 2015). We obtained regression weights using the *summary* function of the *lme4* package, *F* statistics and *p* values (Satterthwaithe approximation) using the *anova* function of the *car* and *lmerTest* packages (Fox & Weisberg, 2010), and normed means, standard deviations, and standard errors using the *summarySEwithin* function of the *Rmisc* package (Morey, 2008).

Results and Discussion

The temporal expansion hypothesis predicts that people will judge the chord sequences that contain oddballs as longer than those that do not, regardless of whether people are engaged in relatively temporal or nontemporal information processing.

In contrast, the RAM predicts that when people are engaged in relatively temporal information processing, they will judge the chord sequences that contain oddballs as shorter than those that do not, but when people are engaged in relatively nontemporal information processing, they will judge the chord sequences that contain oddballs as *longer* than those that do not.

Specifically, the RAM predicts that in the present experiment (a) people will verbally estimate the chord sequences that contain oddballs as shorter, but reproduce with musical imagery the chord sequences that contain oddballs as longer, than those that do not, and (b) people will judge the repeated chord sequences that contain oddballs as shorter, the incoherent chord sequences that contain oddballs as longer, and the coherent chord sequences that contain oddballs as neither shorter nor longer, than those that do not.

Furthermore, the RAM predicts that the effects of response type and event structure will compound, such that (c) the finding that people verbally estimate the chord sequences that contain oddballs as shorter than those that do not will be more robust when those chord sequences are repeated than when they are coherent, which in turn will be more robust than when they are incoherent, and (d) the finding that people reproduce with musical imagery the chord sequences that contain oddballs as longer than those that do not will be more robust when those chord sequences are incoherent than when they are coherent, which in turn will be more robust than when they are repeated.

As predicted by the RAM, we found an oddball X response type interaction, $F_{(1, 7251.36)} = 37.41$, $p < .0001$ (see Figure 5). People verbally estimated the chord sequences that contained oddballs ($M = 0.932$; $SD = 0.238$) as shorter than those that did not ($M = 0.957$; $SD = 0.242$), $\beta = -.0245$, $t_{(161)} = -3.99$, $SE = 0.0062$, $p = .0001$, but reproduced with musical imagery the chord sequences that contained oddballs ($M = 0.969$; $SD = 0.291$) as longer than those that did not ($M = 0.943$; $SD = 0.276$), $\beta = .0254$, $t_{(161)} = 4.12$, $SE = 0.0062$, $p < .0001$. These results show how oddballs shorten the subjective duration of chord sequences when people are engaged in relatively temporal information processing (verbal estimations), but lengthen the subjective duration of chord sequences when people are engaged in relatively nontemporal information processing (musical imagery reproductions).

Also in line with the RAM, we found an omnibus oddball X event structure interaction, $F_{(2, 7249.99)} = 3.01$, $p = .049$ (see Figure 6). This interaction was driven by the difference between the effects of oddballs on the repeated chord sequences and those on the incoherent chord sequences, $\beta = -0.0103$, $t_{(7250)} = -2.05$, $SE = .005$, $p = .040$, and the difference between the effects of oddballs on the repeated chord sequences and those on the coherent chord sequences, $\beta = -0.0110$, $t_{(7250)} = -2.20$, $SE = .005$, $p = .028$. The effects of oddballs were more negatively related to the repeated chord sequences than they were to the incoherent and coherent ones. People appeared to judge the repeated chord sequences that contained oddballs as shorter than those that did not (this difference was not significant at $p = .064$). These results further show how the degree to which people are engaged in relatively temporal or nontemporal information processing can shape the subjective duration-distorting effects of attention-capturing stimuli.

Although the oddball X response type X event structure interaction was not significant, the influence of event structure on the effects of oddballs appeared to emerge only when people were making musical imagery reproductions. The oddball X event structure interaction was significant when people were making musical imagery reproductions, but not when they were making verbal estimations. In the musical imagery reproduction condition, the effects of oddballs were more positively related to the incoherent chord sequences than they were to the repeated ones, $\beta = .0381$, $t_{(7259)} = 2.69$, $SE = .0142$, $p = .007$, and more positively related to the coherent chord sequences than they were to the repeated ones, although this difference was not significant at $p = .067$ (see Figure 7). People reproduced with musical imagery both the incoherent chord sequences that contained oddballs ($M = 0.961$; $SD = 0.225$) as longer than those that did not ($M =$

0.932; *SD* = 0.216), β = .0421, $t_{(1113)} = 4.12$, *SE* = .0102, $p < .0001$, and the coherent chord sequences that contained oddballs (*M* = 0.955; *SD* = 0.215) as longer than those that did not (*M* = 0.941; *SD* = 0.210), β = .03, $t_{(1107)} = 2.93$, *SE* = .0102, $p = .003$. These results offer some additional evidence to support the RAM, and offer the possibility that the influence of event structure on the effects of musical oddballs depend on musical imagery.

We also found a main effect of event structure, $F_{(2, 29.88)} = 4.22$, $p = .024$, and an event structure X response type interaction, $F_{(1, 7250.08)} = 9.80$, $p < .0001$. People reproduced with musical imagery the repeated chord sequences (*M* = 0.977; *SD* = 0.274) as longer than both the coherent ones (*M* = 0.942; *SD* = 0.259), $t_{(830)} = 4.964$, *SE* = .0071, $p < .0001$, and the incoherent ones (*M* = 0.949; *SD* = 0.273), $t_{(850)} = 3.681$, *SE* = .0074, $p < .001$; these differences did not emerge when people were making verbal estimations. These results highlight the fact that the coherent and incoherent chord, but not the repeated, sequences that contained oddballs were reproduced with musical imagery as longer than those that did not.

Finally, we found a main effect of duration, $F_{(2, 9)} = 19.51$, $p < .001$, and a duration X response type interaction, $F_{(2, 11.62)} = 36.31$, $p < .0001$. People verbally estimated the 3.5 s chord sequences (*M* = 0.995; *SD* = 0.243) as longer than both the 7 s ones (*M* = 0.936; *SD* = 0.212), β = .0605, $t_{(9)} = 3.138$, *SE* = .0193, $p = .012$, and the 12 s ones (*M* = 0.903; *SD* = 0.216), β = .0927, $t_{(9)} = 4.81$, *SE* = .0193, $p < .001$. On the other hand, people reproduced with musical imagery the 12 s chord sequences (*M* = 0.849; *SD* = 0.231) as shorter than both the 3.5 s ones (*M* = 1.04; *SD* = 0.283), β = -.1308, $t_{(9)} = -4.74$, *SE* = .0276, $p = .001$, and the 7 s ones (*M* = 0.979; *SD* = 0.248), β = -.1918, $t_{(9)} = -6.96$, *SE* = .0276, $p < .0001$; people appeared to reproduced with musical imagery the 7 s chord sequences as shorter than the 3.5 s ones (this difference was not significant at *p* = .054). These findings are in line with Vierordt's law, and suggest that verbal estimations are more resistant to underestimations than musical imagery reproductions.

No effects of oddball placement or formal musical training emerged. We found similar patterns of results when analyzing these data with the outliers included.

Experiment 2

The findings of experiment 1 lend considerable evidence in support of the RAM. The response type manipulation yeilded a robust interaction in the direction predicted by the RAM, and similar patterns of effects emerged when manipulating event structure. Event structure, however, appeared to influence the effects of oddballs in experiment 1 only when people were making musical imagery reproductions, and not when they were making verbal estimations. To further examine the influence of event structure on the subjective duration-distorting effects of oddballs in experiment 2, we included only musical imagery reproductions.

In addition to varying event structure in experiment 2, we manipulated the degree to which people were engaged in relatively temporal or nontemporal information processing by varying event familiarity; we included half of the chord sequences in an experimental exposure phase. Familiar events are veridically predictable, consume relatively few attentional resources, and facilitate early stages of information processing (Avant, Lyman, & Antes, 1975; see also Avant & Lyman, 1975). Stimuli that require relatively little cognitive capacity facilitate temporal information processing (Zakay, 1993). This is because reductions in nontemporal information processing load free attentional resources to process temporal information (Zakay & Block, 1995)—psychological time is extraordinarily sensitive to manipulations of attention (Brown, 2008). For the above reasons, Block, Hancock, and Zakay (2010) emphasized the importance that familiarity might have on duration judgments. In line with the RAM, Block et al. expected that familiarity would have opposite subjective duration-distorting effects in prospective and retrospective conditions—conditions that facilitate temporal and nontemporal information processing, respectively (Zakay, 1989).

In experiment 2, we manipulated the degree to which people were engaged in relatively temporal or nontemporal information processing by varying (a) whether chord sequences were repeated, coherent, or incoherent (as in experiment 1), and (b) whether those chord sequences were familiar or unfamiliar.

Method

Participants. A total of 57 undergraduate students enrolled in General Psychology at the University of Arkansas volunteered to participate in this experiment in exchange for course credit. We excluded from the analysis the data of 1 participant who reported abnormal hearing. The remaining 56 (38 females) participants ranged from 18 to 23 years of age (*M* = 19.66; *SD* = 1.25). None were music majors, but 10 had received formal musical training for at least 1 year, ranging from 1 to 11 years (*M* = 3.35; *SD* = 3.27). None had participated in experiment 1. All of the participants gave informed consent before participating in this experiment. This experiment was approved by the University of Arkansas IRB.

Stimuli. We reused the stimuli from experiment 1, with some modifications: We shortened the actual durations of the 12 s and 7 s chord sequences to 8 s and 6 s, respectively—and excluded the 3.5 s ones, altogether—to preserve the overall length of experiment 1. Whereas experiment 1 included 72 unique chord sequences, experiment 2 included only 48. We held all other factors identical to experiment 1.

Procedure. The first block of experiment 2 was an exposure phase. We randomly presented to participants a series of 288 chord sequences (24 unique chord sequences played 12 times each), and instructed participants to listen carefully to each one because important tasks would follow.[13]

In the second block, participants reproduced with musical imagery each of the 48 unique chord sequences (half of which were presented in the exposure phase and half of which were not). Immediately upon the closure of the chord sequence in each of the 48 trials, participants were presented with the on-screen instructions: “Imagine that same clip playing back in your head. Re-play it the same way you heard it, from beginning to end. Left-click to begin your imagined clip, then right-click when it ends.”

All other aspects of the procedure were identical to those of experiment 1.

Data Analysis. The four within-subjects fixed-effects factors were oddball (yes or no), event structure (repeated, coherent, or incoherent), event familiarity (familiar or unfamiliar), and actual duration (6 s or 8 s). The covariate was formal musical training (had or had not received training for at least 1 year). The random effects were subject (56 levels) and item (base chord progression; four levels). The data consisted of 2688 normally distributed ratio scores, 15 of which were identified as outliers using the generalized extreme studentized deviate method, and excluded from the analysis. The final converged model included the random slope of oddball with the subject grouping variable, and the random slopes of event structure and event familiarity with the item grouping variable. Pseudo-R^2 was .495; the intercorrelation coefficients for subjects and items were .352 and .045, respectively.

All other aspects of the data analysis were identical to those of experiment 1.

Results and Discussion

The temporal expansion hypothesis predicts that people will judge the chord sequences that contain oddballs as longer than those that do not**,** regardless of whether people are engaged in relatively temporal or nontemporal information processing.

The RAM predicts that when people are engaged in relatively temporal information processing, they will judge the chord sequences that contain oddballs as shorter than those that do not, but when people are engaged in relatively nontemporal information processing, they will judge the chord sequences that contain oddballs as longer than those that do not.

Specifically, the RAM predicts that in the present experiment (a) people will reproduce with musical imagery the repeated chord sequences that contain oddballs as shorter, the incoherent chord sequences that contain oddballs as longer, and the coherent chord sequences that contain oddballs as neither shorter nor longer, than those that do not, and (b) people will reproduce with musical imagery the familiar chord sequences that contain oddballs as shorter, but the unfamiliar chord sequences that contain oddballs as longer, than those that do not.

Moreover, the RAM predicts that the effects of event structure and event familiarity will compound, such that (c) the finding that people reproduce with musical imagery the repeated chord sequences that contain oddballs as shorter than those that do not will be more robust when those chord sequences are familiar than when they are unfamiliar, and (d) the finding that people reproduce with musical imagery the incoherent chord sequences that contain oddballs as longer than those that do not will be more robust when those chord sequences are unfamiliar than when they are familiar.

As predicted by the RAM, we found an omnibus oddball X event structure interaction, $F_{(2, 2535.68)} = 8.02, p < .001$ (see Figure 8). This interaction was driven by the difference between the effects of oddballs on the repeated chord sequences and those on the incoherent ones, $\beta =$

.0307, $t_{(2535)} = 3.66$, $SE = .0084$, $p < .001$, and the difference between the effects of oddballs on the repeated chord sequences and those on the coherent ones, $\beta = .0272$, $t_{(2536)} = 3.245$, $SE = .0084$, $p = .001$. People judged the repeated chord sequences that contained oddballs ($M = 0.912$; $SD = 0.199$) as shorter than those that did not ($M = 0.946$; $SD = 0.192$), $t_{(349.3)} = -2.72$, $SE = .0124$, $p = .007$, but the incoherent chord sequences that contained oddballs ($M = 0.901$; $SD = 0.195$) as longer than those that did not ($M = 0.929$; $SD = 0.203$), $t_{(349.8)} = 2.24$, $SE = .0124$, $p = .026$; the difference between the subjective duration of the coherent chord sequences that contained oddballs and those that did not was not significant. These findings show how oddballs shorten the subjective of intervals when people are engaged in relatively temporal information processing (repeated chord sequences), but lengthen the subjective of intervals when people are engaged in relatively nontemporal information processing (incoherent chord sequences).

Although the oddball X event structure X event familiarity interaction was not significant, people reproduced with musical imagery the repeated chord sequences that contained oddballs ($M = 0.918$; $SD = 0.189$) as shorter than those that did not ($M = 0.957$; $SD = 0.175$) when they were familiar, $t(1018) = -2.301$, $SE = .0172$, $p = .022$, but this difference was not significant when they were unfamiliar (see Figure 9). This result offers an additional piece of evidence to support the RAM, suggesting that familiar repeated sequences facilitate temporal information processing more effectively than unfamiliar ones.

Similar to experiment 1, in line with Vierordt's law, we found a main effect of duration, $F_{(1, 2.06)} = 35.53$, $p = .026$. People judged the 8 s chord sequences ($M = 0.881$; $SD = 0.248$) as shorter than the 6 s ones ($M = 0.965$; $SD = 0.252$), $\beta = -.0419$, $SE = .0071$.

No effect of formal musical training emerged. We found similar patterns of results when analyzing these data with the outliers included.

General Discussion

Summary

Empirical research has advanced our understanding of psychological time. Findings continue to be contradictory, however, and debates between major schools of thought are ongoing. The present research aimed to test the competing predictions of the temporal expansion hypothesis and the RAM. The temporal expansion hypothesis predicts that the inclusion of oddballs in intervals will lengthen subjective duration. But the RAM predicts that the inclusion of oddballs in intervals will both shorten and lengthen subjective duration, depending on the degree to which people are engaged in relatively temporal or nontemporal information processing. We varied whether intervals were composed of chord sequences did or did not contain oddballs, and manipulated the degree to which people were engaged in relatively temporal or nontemporal information processing by varying response type, event structure, and event familiarity.

Experiment 1 revealed a robust oddball X response type interaction. In line with the predictions of the RAM, oddballs shortened subjective duration when people were making verbal estimations (relatively temporal information processing), but lengthened subjective duration when people were making musical imagery reproductions (relatively nontemporal information processing).

Both experiment 1 and experiment 2 revealed significant oddball X event structure interactions. Again in line with the RAM, oddballs shortened subjective duration when people were presented with repeated chord sequences (relatively temporal information processing), but lengthened subjective duration when people were presented with incoherent chord sequences (relatively nontemporal information processing).

The oddball X event structure interaction in experiment 1 appeared to be specific to the musical imagery reproductions, and the oddball X event structure interaction found in experiment 2 (where people only made musical imagery reproductions) was more robust than that found in experiment 1. Hence, the influence of event structure on the effects of oddballs on the subjective duration of intervals seems to emerge primarily when people make musical imagery reproductions. This makes sense because musical event structure is more cognitively salient when people imagine music than when they do not (as was the case in the verbal estimation condition in experiment 1). This conclusion is of course tentative because the oddball X event structure X response type interaction in experiment 1 was not significant.

We did not find an oddball X event familiarity interaction in experiment 2. Block et al. (2010) can explain this null finding. These researchers conducted a meta-analysis of over 100 experiments and found that event familiarity did not affect time judgments in prospective experiments (such as the ones under current investigation). Block et al. reasoned that familiarity both frees attentional resources by facilitating information processing and consumes attentional resources by increasing memory search and the amount of retrievable associations. In this way, the contradictory influences of familiarity on the allocation of attentional resources effectively cancel each other out. This may also explain why other researchers have found weak or no effects of stimulus familiarity (see Schiffman & Bobko, 1977).

An alternative explanation for why we found no effect of event familiarity is that event familiarity, as a factor, does not effectively manipulate the degree to which people are engaged in relatively temporal or nontemporal information processing—that the confirmation of veridical expectations does not facilitate temporal information processing as effectively as the confirmation of schematic expectations (such as ones manipulated by varying event structure). It is also possible that the particular way in which we manipulated event familiarity was not strong enough to produce any meaningful influence on the effects of oddballs.

To preserve experimental control, we were limited to exposing people to excerpts during their laboratory session. We ran a preliminary study to determine that 12 randomly-ordered repetitions of each unique chord sequence was sufficient to make the chord sequences that had been included in an exposure phase significantly more familiar than ones that had not. However, the pilot study exposure phase included 144 chord sequences, whereas experiment 2 included 288 chord sequences. It might be the case that 12 repetitions are enough to familiarize people with chord sequences when the exposure phase includes only 144 chord sequences, but not when the exposure phase includes 288 chord sequences. Also, the exposure phase in experiment 2 lasted over 33 min—boredom and fatigue might have made it especially difficult to listen carefully to every chord sequence.

It is also possible that experimental exposure phases, themselves, might not be able to make music familiar *enough* to influence information processing in any reliable ways. People become deeply familiar with favorite songs over hundreds of listenings over many years. Researchers studying the effects of preexposure, latent inhibition, and similarity on subjective duration have noted that multiple preexposures are required for significant subjective duration-distorting effects to emerge (Zakay, 1989; see also Kowal, 1987). Future research might benefit from using preexisting music with which people are maximally familiar.

The event structure X response type interaction in experiment 1 showed that the repeated chord sequences were reproduced with musical imagery, but not verbally estimated, as longer than both the coherent and incoherent ones. Brown and Boltz (2002) found similar results when varying mental workload and musical event structure. Both of their experiments were prospective, hence participants were engaged in relatively temporal information processing. Although greater mental workload and incoherent event structure compounded to shorten subjective duration, the incoherent melodies were not judged as shorter than the coherent ones. The present research adds to these findings by showing how repeated, in addition to coherent and incoherent, musical sequences affect subjective duration. The repeated chord sequences in experiment 1 were reproduced with musical imagery as longer (more accurate) than both the coherent and incoherent ones.

The reason that we did not find an event structure X response type interaction in experiment 2, as we did in experiment 1, appears to be that only in experiment 2 were the repeated chord sequences that contained oddballs reproduced with musical imagery as shorter than those that did not. Experiment 2 included a familiarity exposure phase that served to facilitate temporal information processing, whereas experiment 1 did not. Moreover, in experiment 2, only the difference between the *familiar* repeated chord sequences in experiment 2 that contained oddballs and those that did not was significant. This latter finding lends the possibility that the repeated sequences and the familiarity exposure phase compounded to facilitate temporal information processing.

Schiffman and Bobko (1977) similarly studied the potential compounding effects of repetition and familiarity, and alsofound no significant effects. These researchers presented participants color transparencies that contained either homogenous familiar, heterogeneous familiar, or heterogeneous unfamiliar stimuli. The homogenous familiar stimuli, analogous to the familiar repeated chord sequences in the present studies, were repeated household items (e.g., a series of eight identical apples); the heterogeneous familiar stimuli, comparable to the familiar incoherent chord sequences in the present studies, were assorted household items (e.g., table, pencil, light bulb); the heterogeneous unfamiliar stimuli, comparable to the unfamiliar incoherent chord sequences in the present experiments, were assorted unrecognizable items. Participants prospectively reproduced the durations of the slides (5 s, 9 s, 13 s, 17 s). Schiffman and Bobko found no effects of familiarity, reasoning that their manipulation of familiarity might have not been effective. These findings further suggest that researchers must produce strong manipulations of familiarity to find subjective duration-distorting effects.

In experiment 2, we found a main effect of duration, such that the 8 s chord sequences were more underestimated than the 6 s ones. We found a similar result in experiment 1, but the main effect of duration was characterized by a duration X response type interaction. The 12 s chord sequences were judged as longer than the 7 s ones when they were reproduced with musical imagery, but not when they were verbally estimated. This indicates that the tendency for underestimations to strengthen as actual duration lengthens (for relatively long durations) is more pronounced when people make musical imagery reproductions than when they make verbal estimations. This speaks to the accuracy of verbal estimations, and their resistance to an underestimation bias. People can more easily make verbal estimations about relatively long intervals than they can musical imagery reproductions. The energy required to make reproductions, in general, is a function of the actual duration of the to-be-judged interval. Whereas the amount of time it takes to make reproductions lengthens as the durations of the actual intervals lengthen, the amount of time it takes to make verbal estimations do not—it takes no longer to verbally report “22 s” than it does to report “2 s.” Overall, these effects of duration show how relatively long intervals are underestimated to a greater degree than relatively short ones, a finding both in line with Vierordt’s law and expected in time estimation research.

Theoretical Implications

Time estimation models. Both attention- and memory-based models make accurate predictions about subjective duration, but in different contexts. Attention-based models predict oddballs will shorten subjective duration. We found that oddballs shortened subjective duration when people made verbal estimations and were presented with repeated chord sequences, both of which facilitate temporal information processing. Memory-based models, on the other hand, predict oddballs will lengthen subjective duration. We found that oddballs lengthened subjective duration when people made musical imagery reproductions and were presented with incoherent chord sequences, both of which facilitate nontemporal information processing.

It is no coincidence that in the present experiments, the attention-based model predictions were accurate when people were engaged in relatively temporal information processing, whereas the memory-based model predictions were accurate when people were engaged in relatively nontemporal information processing—these patterns of results fit nicely with the tenets of the RAM. The present research manipulated event structure and response type independently. We found some evidence that they interacted to influence the effects of oddballs on subjective duration, but further research is needed to show how factors that manipulate the degree to which people engage in temporal and nontemporal information processing might interact. Discovering interactions of this sort would further support the proposition of the RAM and dynamic attending theory that temporal and nontemporal information processing are interdependent.

Dynamic attending theory. The collection of studies investigating the tenets of dynamic attending theory have manipulated temporal coherence by varying pitch sequences to show how event structure can directly influence subjective duration. We added uniquely to this effort. We manipulated *harmonic* coherence by varying *chord sequences* to show event structure can *indirectly* influence subjective duration. Our findings contribute to the literature surrounding dynamic attending theory by suggesting that (a) variations in the structural characteristics of chord, in addition to pitch, sequences can affect subjective duration, (b) event structure can have indirect, in addition to direct, effects on subjective duration, and (c) the manipulation of temporal, but not harmonic, accents might be needed in order to find direct effects of coherent versus incoherent event structure on subjective duration.

We found an indirect effect of event structure on subjective duration, such that the effects of oddballs on the subjective duration of intervals were contingent upon the event structure of the chord sequences filling those intervals. We did not find a direct effect of event structure on subjective duration between the coherent and incoherent sequences—there were no differences between the subjective duration of the coherent and incoherent chord sequences—suggesting that the manipulation of temporal accents has a more robust effect on subjective duration than the manipulation of harmonic ones. Temporal accents have been manipulated by varying the durations of individual pitches in melodies—such that pitches range from dotted half notes to eighth notes (see Boltz, 1991, 1998; Jones & Boltz, 1989). A temporal accent is created when a musical event has a relatively long duration. In our experiments, the chord sequences did not have temporal accents because each musical event had the same duration.

Dynamic attending theory emphasizes the role that event structure plays in time estimation, and the role that attending level plays in information processing. Analytic attending involves focusing on relatively low-level properties of stimuli. Examples of analytic attending include focusing on each individual event in a sequence as they occur and focusing on the timbre of someone’s voice as they speak. Future-oriented attending, in contrast, involves focusing on relatively high-level structural relationships between temporal and nontemporal properties of events. Future-oriented attending takes place, for example, when people both listen to someone talk and anticipate when they will finish talking, as is done in order to make an appropriately timed response. Future-oriented attending also occurs when we both listen to musical sounds and anticipate the close of musical phrases, such as anticipating the occurrence of tonics following dominants. Future-oriented attending is tightly linked with expectation. We engage in future-oriented attending when we can make predictions about both what events will occur and when they will occur. Coherent event structures facilitate future-oriented attending. Incoherent event structures facilitate analytic attending—people cannot engage in future-oriented, or expectation-informed, attending if there exists no coherent structure from which to form expectations about.

Jones and Boltz (1989) would argue that people were engaged in future-oriented attending during the presentation of the coherent chord sequences in the present experiments. When coherent sequences contained oddballs, the oddballs violated the expectations activated by future-oriented attending. Thus, oddballs in coherent chord sequences not only violated expectations about event probability—oddballs are salient, attention-capturing, low-probability expectancy violations—but also schematic and veridical expectations about musical structure. The oddballs in the coherent sequences created temporal contrasts. A temporal contrast is created when an actual outcome is different from an expected outcome. In the coherent chord sequences that contained oddballs, expected outcomes about the structure of the music were violated when the oddballs occurred.

In the incoherent chord sequences in the current studies, people were engaged in analytic attending. Here, the oddballs only violated expectations about probability—there existed no future-oriented expectations to violate. The temporal contrasts created by oddballs in the incoherent chord sequences were theoretically weaker than those created by oddballs in the coherent chord sequences. If oddballs constituted weaker expectancy violations in the incoherent compared to coherent chord sequences, then we should have found that the inclusion of oddballs in the chord sequences had a relatively robust effect on the coherent chord sequences. We found effects to the contrary: the incoherent chord sequences that contained oddballs were judged as longer than those that did not *more often* than the coherent chord sequences that contained oddballs were judged as longer than those that did not.

Dynamic attending theory can nonetheless account for this pattern of results by highlighting the role of perceptual grouping, or chunking: The incoherent chord sequences were affected by oddballs to a greater degree than the coherent ones because the incoherent ones facilitated perceptual chunking more than the coherent ones. People used analytic attending (e.g., chunking each chord as an event) when listening to the incoherent chord sequences, but used future-oriented attending (e.g., chunking each musical phrase as an event) when listening to the coherent ones. In this way, people might have imagined the incoherent chord sequences as having relatively many chunks, thereby producing relatively long musical imagery reproductions.

Another possible reason why oddballs had a greater effect on the incoherent, compared to coherent, chord sequences is that attending level shifted in the coherent ones, but did not shift in the incoherent ones. In the coherent chord sequences, oddballs shifted the level of attending from future-oriented to analytic, and thus violated any future-oriented musical expectations that may have formed leading up to the occurrence of the first oddball. In the incoherent chord sequences, on the other hand, oddballs did not shift the level of attending—attending was analytic both before and after the occurrence of the first oddball.

Attending level shifts can affect memory, and musical imagery reproductions involve retrieving and rehearsing information from memory. If people listened to the coherent chord sequences that did not contain oddballs with future-oriented attending, then they likely remembered and imagined them with that same future-oriented attending. But when these coherent chord sequences contained oddballs, future-oriented attending was disrupted and shifted to analytic attending. Accordingly, imaginings of those sequences were likely disrupted and fragmented, producing relatively short and inaccurate musical imagery reproductions. In contrast, if people listened to both the incoherent chord sequences that contained oddballs and those that did not with only analytic attending, then they likely remembered and imagined both with analytic attending. In this way, memory for the incoherent chord sequences that contained oddballs was not as disrupted and fragmented as memory for the coherent ones, thus producing relatively long and accurate musical imagery reproductions.

Dynamic attending theory can also provide an explanation for the present finding that the coherent and incoherent chord sequences that contained oddballs were judged as longer than those that did not. Jones and Boltz (1989) showed that musical melodies that were experimentally manipulated to seem to end later than expected—by changing the event structure of pitch sequences—were duration reproduced as longer than melodies that were manipulated to seem to end on time. Likewise, they showed that melodies that seemed to end too soon were duration reproduced as shorter than those that seemed to end on time. If, in the present research, the inclusion of oddballs made the chord sequences seem to end too late, then this might explain why the chord sequences that contained oddballs were reproduced with musical imagery as longer than those that did not.

There are a number of reasons why the inclusion oddballs in the present experiments might have made the chord sequences seem to end too late. People might have formed the veridical expectation that the chord sequences will end after the occurrence of the first oddball—

the final event of all of the chord sequences that contained oddballs was always an oddball, not a chord. The 3.5 s chord sequences contained only one oddball, which closed the sequence. The 7 s and 12 s chord sequences, in contrast, contained multiple oddballs. Where people might have expected the the 7 s and 12 s sequences to end upon the occurrence of the first oddball, the sequences continued to play chords, perhaps seeming to play for too long, or seeming to end too late.

Future research might explore this possibility by including only one oddball in all of the chord sequences, or by varying whether or not the final event of the chord sequences is an oddball or a chord. If people do veridically expect oddballs to close sequences, then sequences that end with chords—regardless of whether or not they contain oddballs—should be reproduced as shorter than those that end with oddballs. Of course, sequences can be made to seem to end too early by manipulating event structure, itself. For example, ending sequences on dominant, rather than tonic, chords should leave the schematic expectation that tonics close musical phrases unfulfilled, and thus make sequences seem to end too early and be judged as relatively short.

Dynamic attending theory and repeated sequences. The present research offers the unique opportunity to discuss the tenets of dynamic attending theory in the novel context of repeated sequences, and the role of expectations for repeated events, in general. The repeated chord sequences in the present research were all the same—they all consisted of a repeated C Major chord. Do repeated sequences such as these facilitate analytic or future-oriented attending? To answer this question, let us consider how repeated sequences might affect musical expectations. Do repeated sequences confirm or violate musical expectations? Do they differentially manipulate schematic and veridical expectancies?

On the one hand, the repeated sequences in the present research violated the schematic expectation that, in general, music will progress. People enculturated to music in western society schematically expect music to change over time—people rarely hear single musical events repeated on end. On the other hand, the repeated sequences in the present research confirmed the veridical expectation that the repeated sequences in this particular experiment will repeat. People presented with the repeated sequences heard a C Major chord followed by the same C Major chord, again and again. Each subsequent C Major chord confirmed the veridical expectation that the next chord in the sequence would be the same as the one before it. Repeated sequences in the current research thus manipulated schematic and veridical expectations in opposite ways. The repeated sequences violated deeply-engrained schematic expectations about western tonal music, in general, while confirming locally-created veridical expectations about the particular chord sequences in these experiments. The repeated sequences allowed people to anticipate that each subsequent chord in the sequence would be the same: C Major. Furthermore, the chords had an isochronous periodicity—each had the same duration—and people tend to impose subjective accent structures on isochronous sequences (Boltz, 1992, 1994; Fraisse, 1956; Povel, 1981). People in the present studies were able to predict when each subsequent chord would occur. In this way, the repeated sequences offered both high nontemporal predictability about occurrence of the C Major chord, and high temporal predictability about occurrence of that chord at a regular beat period.

To engage in future-oriented attending, people must be able to predict (a) what events will occur, (b) when they will occur, and (c) when the event sequence will *end*. The present repeated sequences, although offering high temporal predictability about the “what” and the “when” of each subsequent event, did not offer the ability to predict ending time.[14] Because the ability to predict ending time is a necessary condition for future-oriented attending, as described by Jones and Boltz (1989), the repeated chord sequences in the present research should have facilitated analytic attending.

This conclusion is in line with the tenets of dynamic attending theory, attention-based models of time estimation, and the RAM, and fits with the findings of the current experiments. Dynamic attending theory posits that future-oriented attending requires being able to anticipate ending times of sequences. Since people in the present research were not able to do so with the repeated sequences, they instead were engaged in analytic attending. When people engage in analytic attending, they focus, among other things, on “counting” each subsequent event. Attention-based models, as well as the RAM, assert that people engaging in counting mechanisms in prospective paradigms (as was the paradigm of the present research) are engaging in temporal information processing; for example, people might treat each counted event as a subjective duration temporal unit, or a second. When people are engaged in temporal information processing, furthermore, attention-capturing events should shorten subjective duration. This is what we found in experiment 2. Attention-capturing events in the present research—oddballs—shortened the subjective duration of the repeated chord sequences.

It is possible that the absence, not presence, of oddballs lengthened the subjective duration of the repeated chord sequences in the present studies. The repeated chord sequences that did not contain oddballs may have seemed to last too long because they violated the schematic expectation that music, in general, will progress. Unfulfilled expectations about harmonic change—that the C Major chord will change to a different chord—might have made the sequences seem to last longer than they should have, or end too late. Also, this sort of delayed gratification—and ultimately unfulfilled expectation—for harmonic change might have enhanced feelings of frustration, which itself can directly lengthen subjective duration (D. T. Miller, 1978).

It is also possible that people were more bored when present with the repeated chord sequences that did not contain oddballs than people were when presented wit those that did contain oddballs. Boredom can emerge when nontemporal information processing load is relatively low (Zakay, 2014). Boring activities or circumstances increase desires to withdraw, and awareness to the passage of time (Csikszentmihalyi, 1990). Boredom lengthens subjective duration—boring experiences seem to last longer than engaging ones. It is possible that the repeated chord sequences that did not contain oddballs in the present research enhanced feelings of boredom—repeated sequences are processed relatively efficiently and consume relatively few attentional resources. Boredom, then, could have directly lengthened the repeated sequences by increasing desires to withdraw from the task, or indirectly lengthened subjective duration by making the repeated sequences seem to go on for too long, or end too late.

Dynamic attending theory and the RAM. It is important to discuss the relationship between temporal and nontemporal information, temporal and nontemporal information processing, and structural coherence. Jones and Boltz (1989) assert that the degree to which temporal information is compatible with nontemporal information is a critical factor in time estimation, yet is often overlooked. Much of the existing time estimation research investigates how nontemporal information influences subjective duration. Researchers should also consider the role of temporal information. Nontemporal information can be organized in time in different ways, and the degree to which these organizations are coherent can influence subjective duration. When do nontemporal events occur in time? How are nontemporal events ordered in time? What are the durations of each nontemporal event, and how does each of their durations correspond with their positions in event sequences? All of these questions concern temporal properties of nontemporal stimuli in our environment. These temporal properties are important to consider, control for, and examine in time estimation research.

When nontemporal events have compatible temporal properties, people no longer perceive them as nontemporal events in isolation, but as nontemporal events informed by their temporal properties. When people order words in ways that form coherent sentences, we no longer perceive word sequences as groups of individual nontemporal verbal events, but rather as coherent utterances intended to communicate semantic meaning. When chords are ordered in ways that follow the rules of western tonal harmony, we no longer perceive them as individual nontemporal chordal events, but rather as coherent musical phrases. Future-oriented attending allows us to make sense of our environment by perceiving structurally coherent stimuli as nontemporal stimuli informed by their corresponding temporal properties. Dynamic attending theory asserts that temporal and nontemporal information are tightly linked—that people engage in an interdependent level of both temporal and nontemporal information processing—in coherent environments.

We argue that the RAM is compatible with dynamic attending theory. The RAM treats the distinction between temporal and nontemporal information processing as merely relative, and acknowledges that both the temporal and nontemporal processors are activated when perceiving coherent stimuli. As Zakay stated:

> The weight assigned to specific information derived from either P(t) [the temporal processor] or P(m) [the nontemporal processor] is a function of the degree of attentiveness of the processor. . . . Temporal information processing takes place at all times, but it is done intermittently when cognitive capacity is not directly focused at P(t); hence, under such conditions, P(t) is assigned a low degree of attentiveness.” (1993, p. 658)

The RAM defines engaging in temporal information processing as attending to high amounts of temporal information, *relative* to nontemporal information—certain amounts of nontemporal information are still perceived and processed. The same is true for the way in which the RAM defines engaging in nontemporal information processing, or when people attend to relatively high amounts of nontemporal information, relative to temporal information.

The types of temporal information processing outlined by the RAM and that outlined by dynamic attending theory are similar in that both involve attending to temporal information, but both differ in important ways: The RAM refers to temporal information processing as that which occurs when people track duration by counting changes, such as seconds. This is usually the case in prospective paradigms, when people track the passage of time in preparation for upcoming duration judgments. Dynamic attending theory, on the other hand, refers to temporal information processing as that which occurs when people attend to temporal information, in general, not necessarily for the sake of tracking the passage of time—such as when focusing on the rhythm of a coherent musical song for the sake of listening to music.

Counting seconds and attending to musical rhythm are not mutually exclusive behaviors, and both involve attending to temporal information, but they are unique in important ways. Each seem to occur under different circumstances. People often focus on the passage of time when asked to judge duration in time estimation experiments, or when engaged in boring, frustrating, or undesirable activities. People often attend to musical rhythm, on the other hand, when listening to, imagining, or performing coherent music. Moreover, focusing on the rhythm of a coherent song facilitates more nontemporal information processing than counting seconds because nontemporal musical properties, such as pitches, timbres, and contour changes, are tightly linked with temporal musical properties (Jones & Boltz, 1989).

In line with the RAM and dynamic attending theory, we treated the distinction between temporal and nontemporal information processing in the present research as relative. Participants were engaged in relatively temporal information processing when making verbal estimations, and in relatively nontemporal information processing when making musical imagery reproductions. Participants were engaged in relatively temporal information processing when listening to repeated chord sequences, and in relatively nontemporal information processing when listening to coherent and incoherent chord sequences. We found that chord sequences that contained oddballs were judged as shorter than those that did not when people were engaged in relatively temporal information processing, and judged as longer than those that did not when people were engaged in relatively nontemporal information processing. The present research is in line with both the RAM and dynamic attending theory, suggesting that temporal and nontemporal information processing are interdependent.

Subjective temporal and nontemporal units. The present investigation found consistent support for the RAM. Nevertheless, when considered in isolation, some of the present findings can be considered as support for the temporal expansion hypothesis. The temporal expansion hypothesis predicts that people will judge chord sequences that contain oddballs as longer than those that did not, and this is what we found when people were engaged in relatively nontemporal information processing. This finding lends the possibility that the temporal oddball illusion is driven by nontemporal, rather than temporal, information processing. Oddball events might be judged as longer than standard events because oddballs increase attention to the oddballs' *nontemporal,* rather than temporal, properties.

This possibility is compatible with the temporal expansion hypothesis. Tse et al. (2004) theorize that oddballs are judged as longer than standards for the following reasons: An oddball captures attention and increases the amount of attentional resources allocated to that oddball, relative to a standard. This enhancement of attention to the oddball increases the rate at which information is processed while perceiving the oddball. Because the rate of information processing increases, the number of "subjective temporal units" stored and counted by a cognitive timer increases. A higher number of units stored and counted during the perception of an oddball than during the perception of a standard makes the oddball seem longer than the standard, or expands the subjective duration of the oddball.

Tse et al. (2004) base the mechanisms driving the temporal oddball illusion on the tenets of attention-based models of short interval time estimation, ones that assert the existence of a counter mechanism that accumulates and tallies the number of subjective temporal units stored in an accumulator (Thomas & Weaver, 1975; Treisman, 1963). These attention-based models predict that attention-capturing stimuli will shorten subjective duration, because when stimuli capture attention, more attention is focused on the nontemporal aspects of the stimuli and less attention is focused on the passage of time. When attention is distracted from the passage of time, the accumulation of subjective temporal units are missed, and fewer units are stored and counted.

Tse et al. (2004) suggest that attention-capturing stimuli can, at the same time as they shorten subjective duration by distracting attention from the passage of time, lengthen subjective duration by increasing the "rate of information processing" of an individual event. When an event captures more attention, it increases the amount of information about that event that is processed. This increases the amount of "subjective temporal units" stored and counted, and thus lengthens the subjective duration of that event. Crucially, Tse et al. liken these subjective temporal units to those articulated by the attention-based models of time estimation, arguing that attention-capturing stimuli (a) decrease the amount of subjective temporal units stored and counted by decreasing the amount of attention allocated to the passage of time, and also (b) *increase* the amount of subjective temporal units stored and counted by increasing the amount of attention allocated to individual nontemporal stimulus events. This proposition might, of course, be contradictory. How can the types of subjective units accumulated in these two scenarios be the same?

To resolve the contradiction stated above, we merged the methodologies of the short interval time estimation and timing literatures and provide evidence to support the proposition that these two scenarios involve the accumulation of essentially different types of information: The former scenario involves the accumulation of subjective temporal units; the latter, subjective nontemporal information. More subjective temporal units are stored and counted when attending to the passage of time by counting seconds and tracking the passage of time. More subjective temporal units are units inferred directly from attending to the passage of time. More subjective nontemporal information, on the other hand, is stored in memory when increasing the rate of information processing of a nontemporal stimulus event; increasing the intensity or loudness of an event, the emotional salience of an event, the level of arousal elicited by an event, or the salience of an expectancy violation, such as an oddball, might increase the rate of information processing and thus nontemporal information stored in memory.

When people are required to make duration judgments retrospectively, or duration judgments about individual subsecond events, subjective nontemporal information is *inferred* based on the amount of time-*unrelated* information perceived and remembered. This is because when people are engaged in relatively nontemporal information processing, they accumulate relatively few subjective temporal units from which to base duration judgments. People must thus resort to making inferences about time's passage based on the available memory traces of nontemporal information.

Oddballs can both distract attention from the passage of time (from the accumulation of subjective temporal units such as seconds) and focus attention on the oddballs, themselves, thereby increasing the rate at which the nontemporal properties of the oddballs are processed and the increasing the amount of perceived and remembered subjective nontemporal information.

In the present research, oddballs decreased the number of subjective temporal units stored and counted when people were engaged in relatively temporal information processing, thereby shortening subjective duration. Oddballs also increased the amount of subjective nontemporal information perceived and remembered when people were engaged in relatively nontemporal information processing, thereby lengthening subjective duration. Specifically, oddballs decreased the number of subjective temporal units stored and counted when people were making verbal estimations, responses that require storing and counting seconds, and when people were presented with repeated chord sequences, stimuli that are processed relatively efficiently and leave relatively many attentional resources available to track time and count seconds. On the other hand, oddballs increased the amount of subjective nontemporal information stored in memory when people were making musical imagery reproductions, responses that encourage attending to and rehearsing nontemporal musical properties, and when people were presented with incoherent chord sequences, stimuli that violate expectations, are processed relatively inefficiently, and leave relatively few attentional resources available to track time.

Our proposed distinction between subjective temporal units and subjective nontemporal information is in line with memory-based models of time estimation, as well as the RAM. These models posit that the more nontemporal information, contextual changes, or high-priority events perceived and remembered during an interval, the longer the subjective duration of that interval should become (Block, 1990; Poynter, 1989). People infer the passage of time from nontemporal information when temporal accents are unavailable or when relying on memory (Boltz, 1989, 1995), as is the case in retrospective designs (Block & Zakay, 1997; Zakay, 1993); people have no temporal information from which to base duration judgments when time judgments are requested retrospectively.

Participants often make hundreds of prospective, not retrospective, time judgments over the course of timing experiments that examine the temporal oddball illusion. Nevertheless, the implications of memory-based models, the RAM, and the present research—that duration judgments about oddballs in timing studies are based on subjective nontemporal information, rather than subjective temporal units—are compatible with the temporal expansion hypothesis.

Although oddballs in timing experiments investigating the temporal oddball illusion are not judged retrospectively, they are judged as single events, and these events have relatively short durations. These experiments require that people judge the durations of individual oddball events. Oddballs that are found to be judged as reliably longer than standards are usually in the range of the perceptual present, or no longer than 5 s. In fact, most conditions in each experiment, as well as most experiments, use oddballs and standards that are shorter than 1 s. Explicit counting serves as a useful time estimation strategy only for intervals that are longer than 1 s (Grondin, Meilleur-Wells, & Lachance, 1999).

If people avoid using counting seconds as a strategy when judging the durations of individual subsecond events, then they would not be able to accumulate subjective temporal units based on seconds, and would thus have to rely on available subjective nontemporal information stored in memory. This interpretation is in line with temporal expansion hypothesis because the temporal expansion hypothesis states that people base duration judgments about individual events on the amount of perceptual—and, as we suggest, nontemporal—information processed. Memory-based models of time estimation state that people base duration judgments about intervals on the amount of nontemporal information processed. The present findings show how both the temporal expansion hypothesis and memory-based models make similar predictions. Both explain the effects of oddballs in the present experiments when people were engaged in relatively nontemporal information processing.

Oddball expansion or standard contraction. There is an ongoing debate in the timing literature between the temporal expansion hypothesis (Tse et al., 2004) and the temporal contraction hypothesis (Eagleman & Pariyadath, 2009; Pariyadath & Eagleman, 2007, 2008a, 2008b, 2012). Tse et al. (2004) argue that oddballs, or unpredictable events, expand subjective duration. Pariyadath and Eagleman (2012) argue that standards, or predictable events, *contract* subjective duration. The temporal contraction hypothesis is supported by studies examining repetition suppression (see Henson & Rugg, 2003; Summerfield & de Lange, 2014; Summerfield, Trittschuh, Monti, Mesulam, & Egner, 2008; Todorovic & de Lange, 2012). Repeated stimuli increase neural efficiency. Pariyadath and Eagleman argue that subjective duration in timing experiments is directly connected to neural activation, such that fewer neural firings lead to shorter subjective experiences. Standards are judged as shorter than oddballs because standards are more predictable, are processed more efficiently, and activate fewer neural firings than oddballs.

Both the temporal expansion and contraction hypotheses predict that people will judge the repeated and coherent chord sequences that contain oddballs in the present experiments as longer than those that do not, but each make different predictions about the effects of oddballs on the incoherent chord sequences. The temporal expansion hypothesis predicts that people will judge the incoherent chord sequences that contain oddballs as longer than those that do not. Oddballs expand subjective duration, hence the inclusion of oddballs in intervals should expand the subjective duration of those intervals. Oddballs increase the number of subjective units stored and counted, hence intervals that include oddballs should have more units stored and counted than intervals that do not.

On the other hand, the temporal contraction hypothesis predicts that people will judge the incoherent chord sequences that contain oddballs as no differently than those that do not. This is because the incoherent chord sequences used in the current experiments are unpredictable—analogous to the unpredictable scrambled number sequences used in Pariyadath & Eagleman (2007; e.g., 1—4—3—5—2). Pariyadath and Eagleman (2012) assert that neural responses are not suppressed in response to unpredictable, scrambled sequences, as they are in response to predictable, ordinal sequences—only predictable sequences contract subjective duration. There were no predictable sequences in either the incoherent chord sequences that contain oddballs or those that do not. Therefore, the temporal contraction hypothesis predicts that we will find no difference between the subjective duration of the incoherent chord sequences that contain oddballs and those that do not.

We found that incoherent chord sequences that contained oddballs were judged as longer than those that did not in both experiments. If both the subjective duration of oddballs as individual events and the subjective duration of oddballs that fill intervals operate under the same mechanisms when people are engaged in relatively nontemporal information processing, then the present research lends evidence to support the temporal expansion hypothesis over the temporal contraction hypothesis.

Conclusion

We used a novel and covert measure of subjective duration—musical imagery reproduction—to facilitate nontemporal information processing in two experiments. We found consistent evidence in support of the RAM. The effects of attention-capturing, high-priority events on the subjective duration of intervals in the present research depended on the degree to which people were engaged in relatively temporal or nontemporal information processing. Oddballs shortened the subjective duration of chord sequences when people were engaged in relatively temporal information processing, but lengthened the subjective duration of chord sequences when people were engaged in relatively nontemporal information processing. These results are in line with the proposition made by dynamic attending theory and the RAM that temporal and nontemporal information processing are interdependent.

In addition, we proposed that the temporal expansion hypothesis accurately accounts for subjective duration when people are engaged in relatively nontemporal information processing, and that oddballs are judged as longer than standards because oddballs increase the accumulation of subjective nontemporal information, rather than "subjective temporal units." In line with this proposal, the effects of oddballs on the subjective duration of the incoherent sequences in the present experiments suggest that oddballs are judged as longer than standards because oddballs expand subjective duration, and not because standards contract subjective duration.

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Footnotes

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[1] This is a tenet of Vierordt's law. Vierordt's law states that people tend to overestimate relatively short intervals and underestimate relatively long intervals (see Lejeune & Wearden, 2009; van Rijn, 2016).

[2] Instructions that do not explicitly state duration appear in the timing literature where studies investigate implicit timing processes. Implicit measures of subjective duration emerge from actions or behaviors (Turvey, 1977), such as running, speaking, and singing (Zelaznik, Spencer, & Ivry, 2002); there is, moreover, an important distinction between explicit and implicit timing processes (Coull & Nobre, 2008).

[3] It is important avoid explicitly stating duration in instructions when manipulating information processing in order to help prevent pre-trial awareness of duration, or temporal information processing. Pre-trial awareness of duration is, after all, the distinguishing characteristic between the two major paradigms used in time estimation experiments (prospective and retrospective), and an important factor in time estimation research, in general.

[4] Some short interval time estimation experiments have made musical imagery an integral part of their duration reproductions (see Boltz, 1995, 1998, 1999; Brown & Boltz, 2002; Firmino & Bueno, 2008, 2013, 2014; Firmino et al., 2009; Jones & Boltz, 1989). Nonetheless, their experimental instructions explicitly state duration or time.

[5] The processing of duration has much in common with the processing of other nontemporal information, such as the physical length of stimuli (Zakay, Bibi, & Algom, 2014).

[6] Imagination, after all, involves creating surface representations of deep structures stored in long-term memory (Kosslyn, 1981).

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[7] Time estimation delay affects information processing because temporal information is most retrievable from memory and most relevant to duration judgments immediately following an interval. The retrievability and relevancy of temporal information degrades as the time between the end of an interval and the beginning of an estimation lengthens. This degradation can, of course, be avoided by intentionally storing temporal information in long-term memory. But researchers can prevent this by requiring that people perform distractor tasks during the delays (Zakay & Fallach, 1984).

[8] Time estimation delay refers to whether estimates are made immediately following the close of an interval (immediate estimation) or after a given amount of time (remote estimation). Time estimation reference refers to whether estimates are based on information stored in short-term memory (absolute estimation) or long-term memory (relative estimations).

[9] This latter finding supports attention-based models because the type of segmentation used in this experiment did not affect nontemporal task demands or attention to the passage of time.

[10] Task switching constitutes alternating attention between different types of task-related stimulus information (e.g., colors or words; Gopher, Armony, & Greenshpan, 2000), and is an important part of executive control (Shallice, 1994).

[11] Oddballs are low-probability events; standards are high-probability events. Examples of an oddball include a circle following a series of squares, or a high-pitched tone following a series of low-pitched tones, where the squares and low-pitched tones are standards. Low-probability, unexpected stimuli capture attention (Sokolov, 1963). Low-probability stimuli demand more attentional resources than high-probability stimuli (Hon & Tan, 2013), and more attention to stimuli lengthen the subjective duration of those stimuli (Seifried & Ulrich, 2011). Oddballs,

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furthermore, have been shown to involuntarily capture both bottom-up and top-down attentional processes (Debener, Kranczioch, Herrmann, & Engel, 2002). Moreover, abrupt, novel, low- and high-pitched events, such as oddballs, produce automatic activation of brain stem reflexes (Goydke, Altenmüller, Möller, & Münte, 2004; Juslin & Västfjäll, 2008) and physiological processes, even in pre-birth infants (Lecanuet, 1996).

[12] Sliding tones are especially salient because they exhibit motion (Brown, 1995).

[13] We ran a pilot study to show that 12 repetitions were sufficient to make the chord sequences familiar. In the pilot study, participants listened carefully to 144 randomly-presented chord sequences in an initial exposure phase (12 unique chord sequences played 12 times each). Then participants made familiarity ratings for each of 24 unique chord sequences (half of which were presented in the exposure phase and half of which were not). The chord sequences that were presented in the exposure phase were rated as significantly more familiar than those that were not.

[14] Expectations that C Major chords will occur at regular periods in time are distinct from expectations about the likelihood that any given C Major chord in the sequence will be the *last* sequential event. The coherent chord sequences offered relatively high temporal predictability about sequence ending time because tonic chords (C Major) following dominant ones (G Major), for instance, confirm schematic expectations and foreshadow musical phrase closure.

Figures

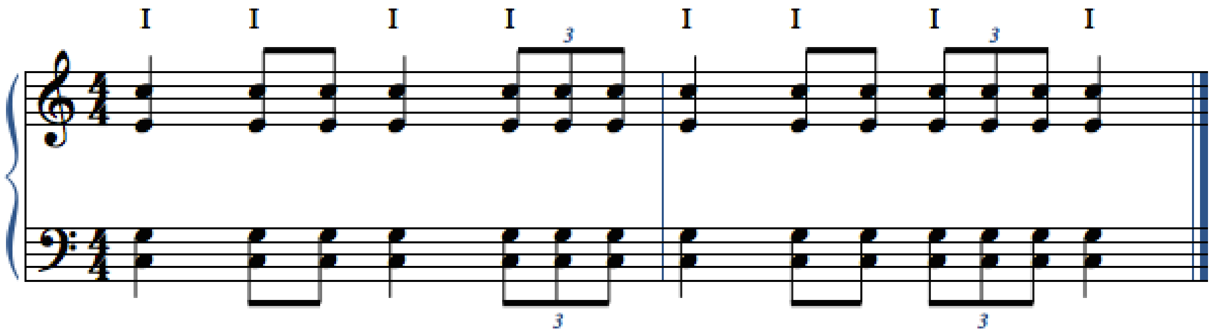


Figure 1. Example of a repeated chord sequence

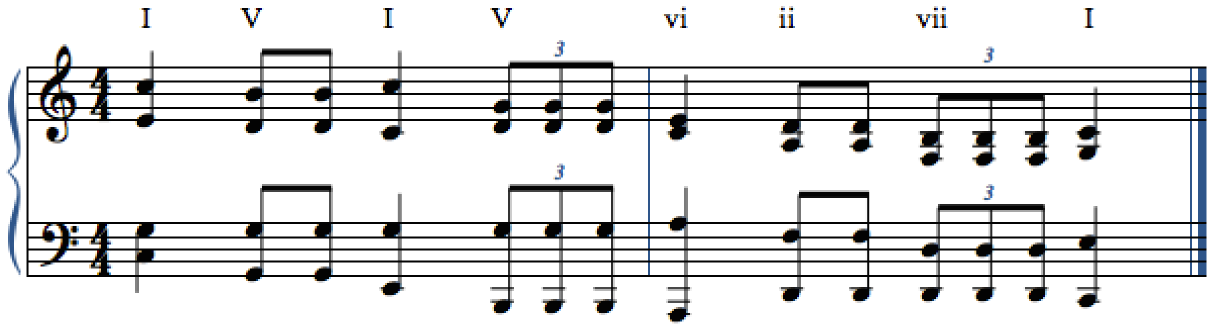


Figure 2. Example of a coherent chord sequence

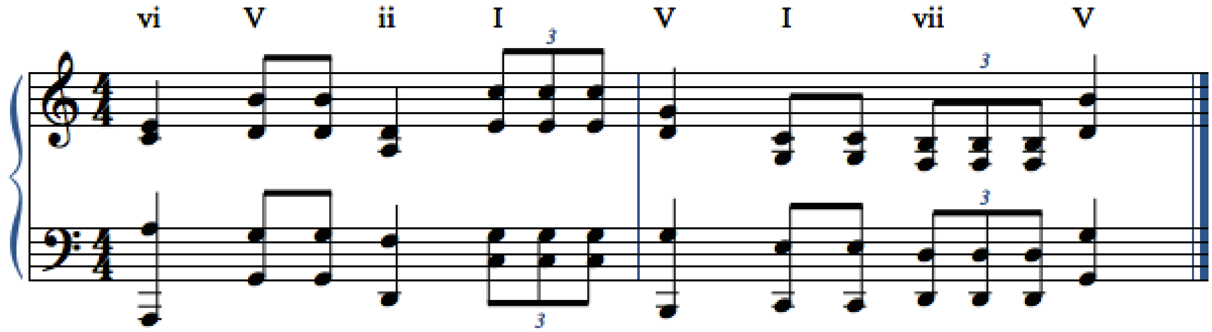


Figure 3. Example of an incoherent chord sequence

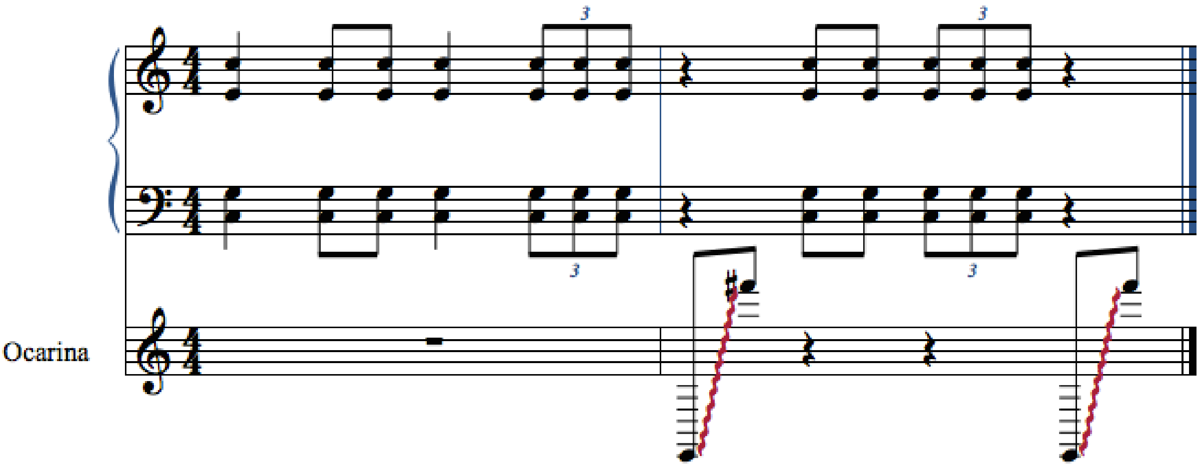


Figure 4. Example of a repeated chord sequence that contains oddballs

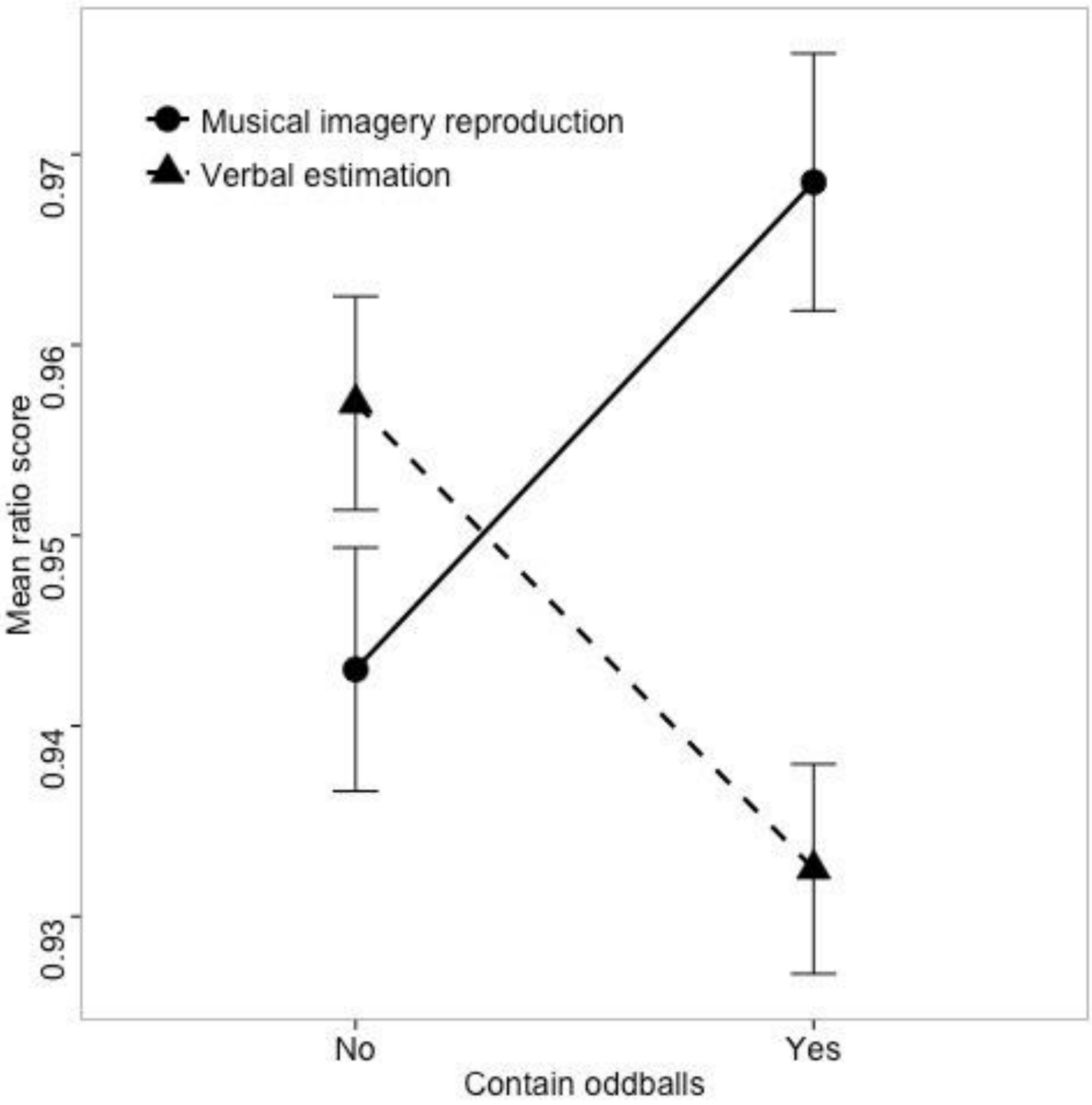


Figure 5. Mean ratio scores (±1 SEM) for the chord sequences that contained oddballs and those that did not as a function of response type in experiment 1

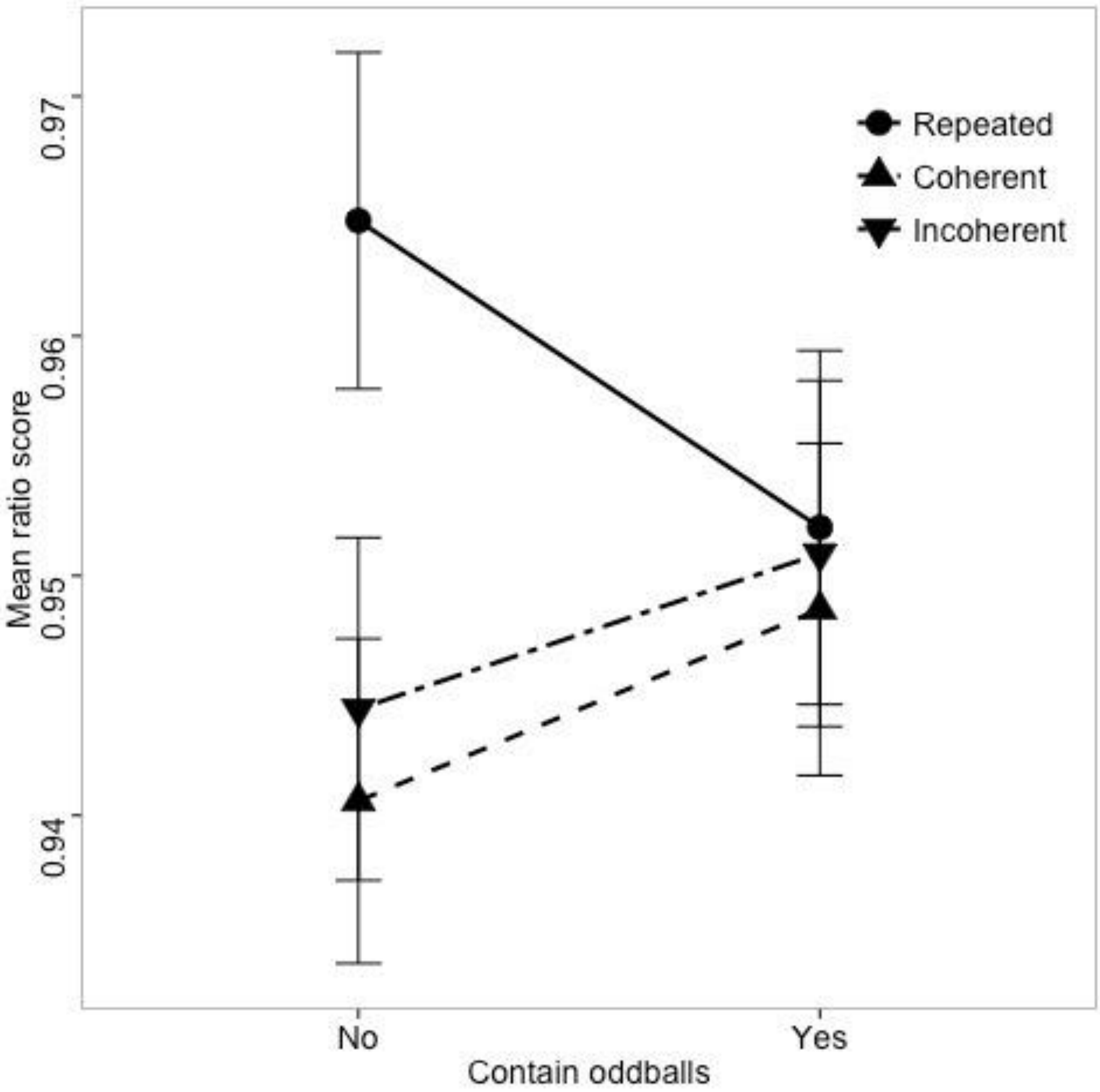


Figure 6. Mean ratio scores (±1 SEM) for the chord sequences that contained oddballs and those that did not as a function of event structure in experiment 1

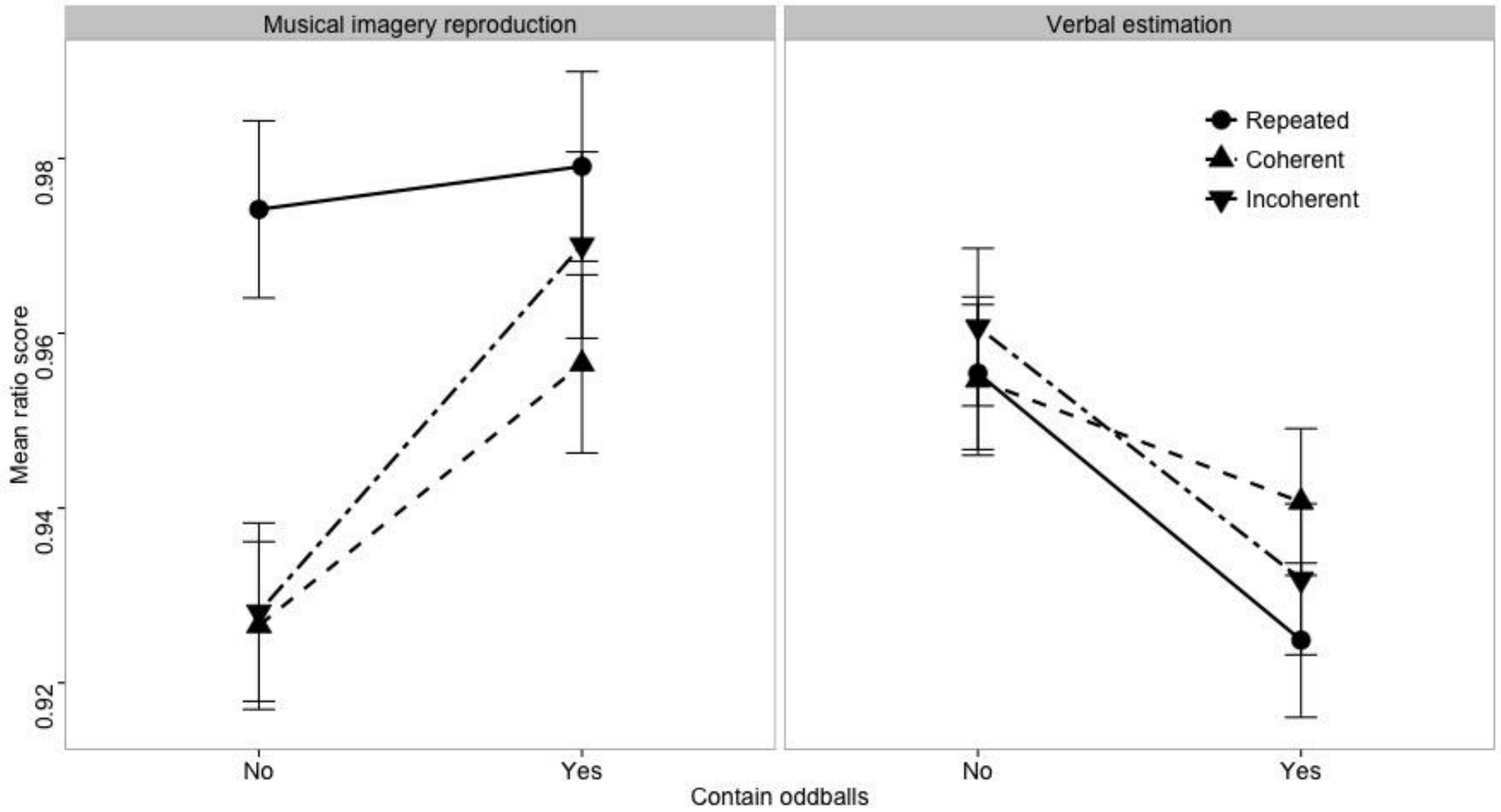


Figure 7. Mean ratio scores (±1 SEM) for the chord sequences that contained oddballs and those that did not as a function of response type and event structure in experiment 1

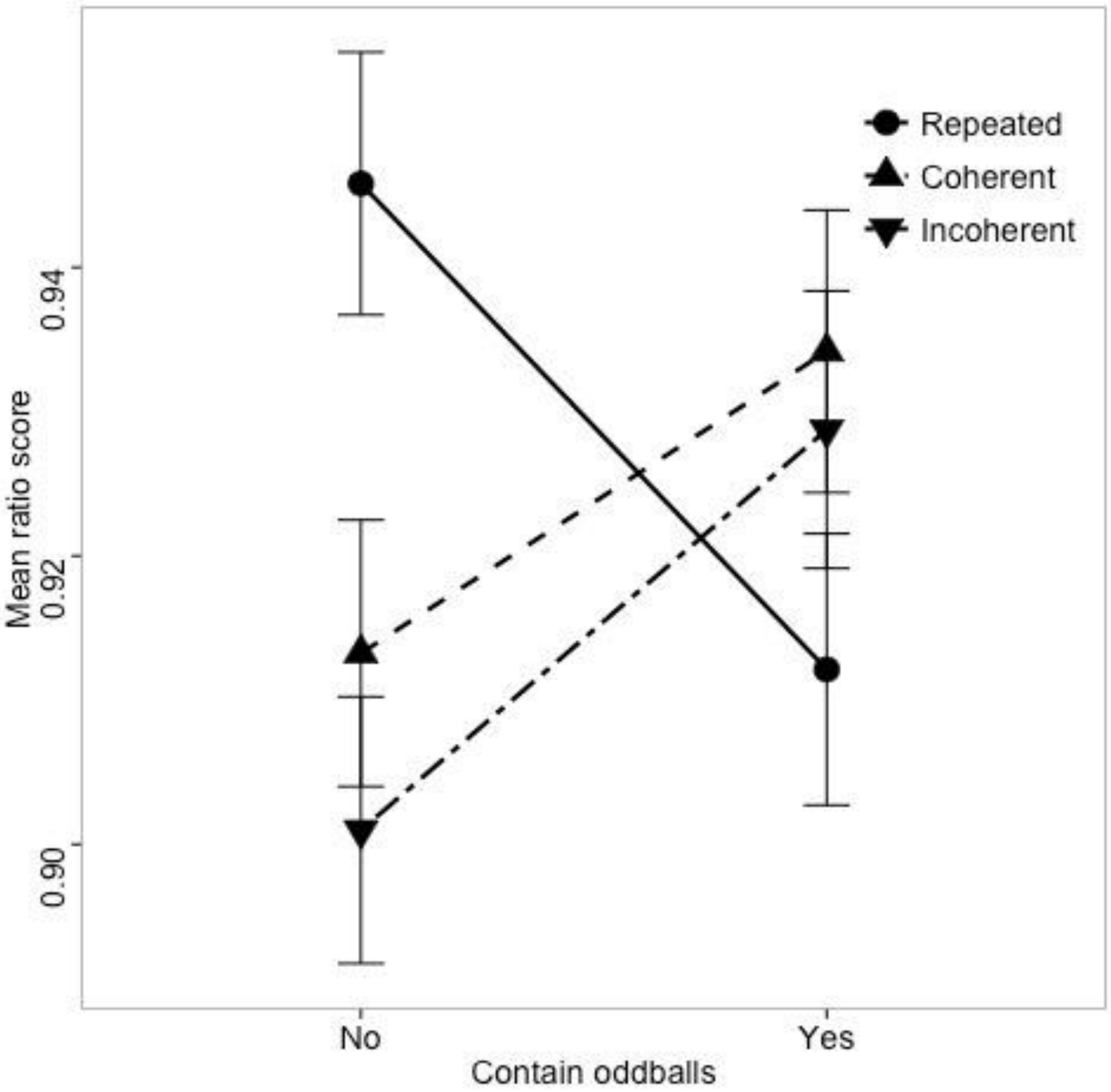


Figure 8. Mean ratio scores (±1 SEM) for the chord sequences that contained oddballs and those that did not as a function of event structure in experiment 2

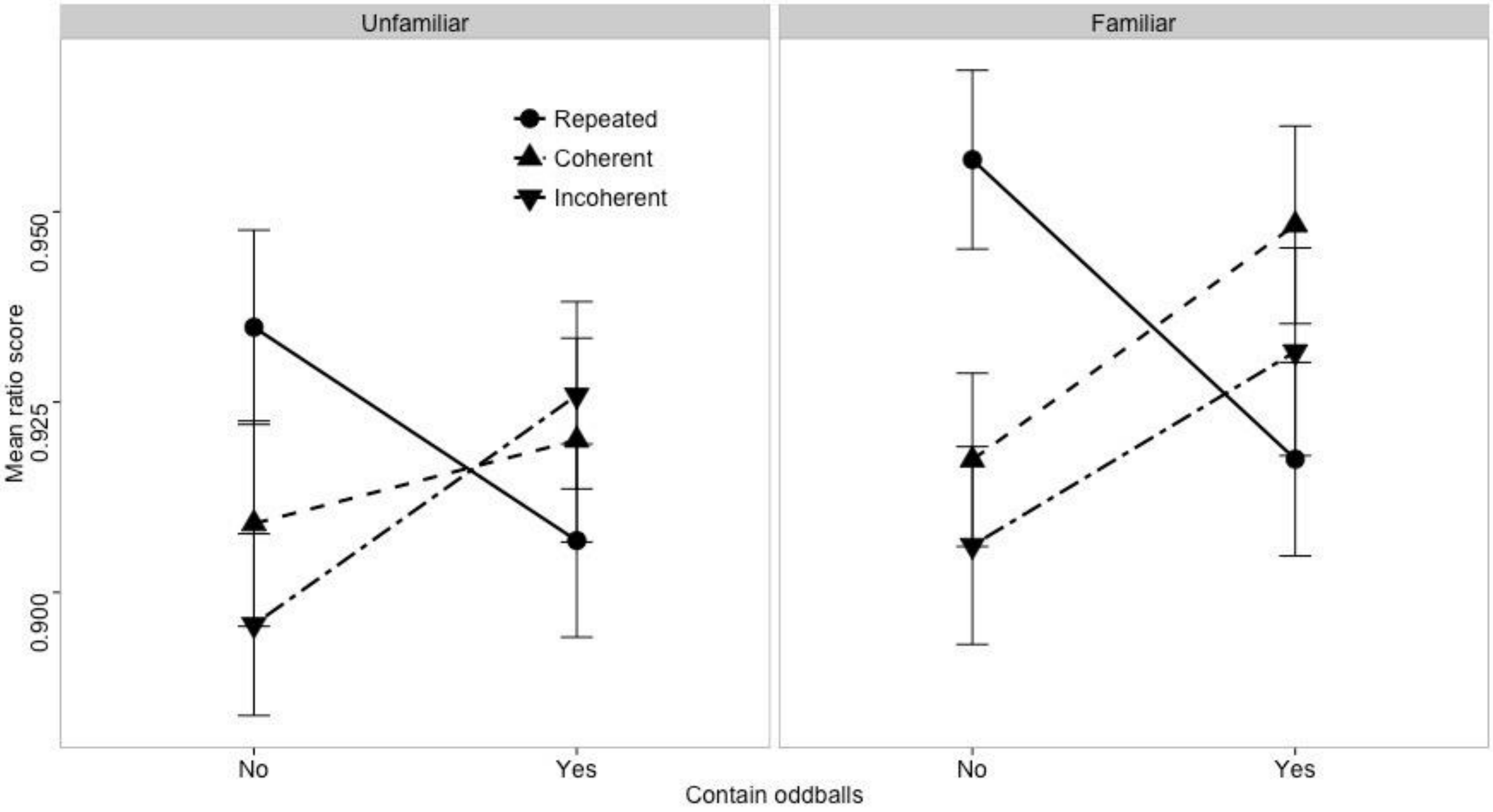
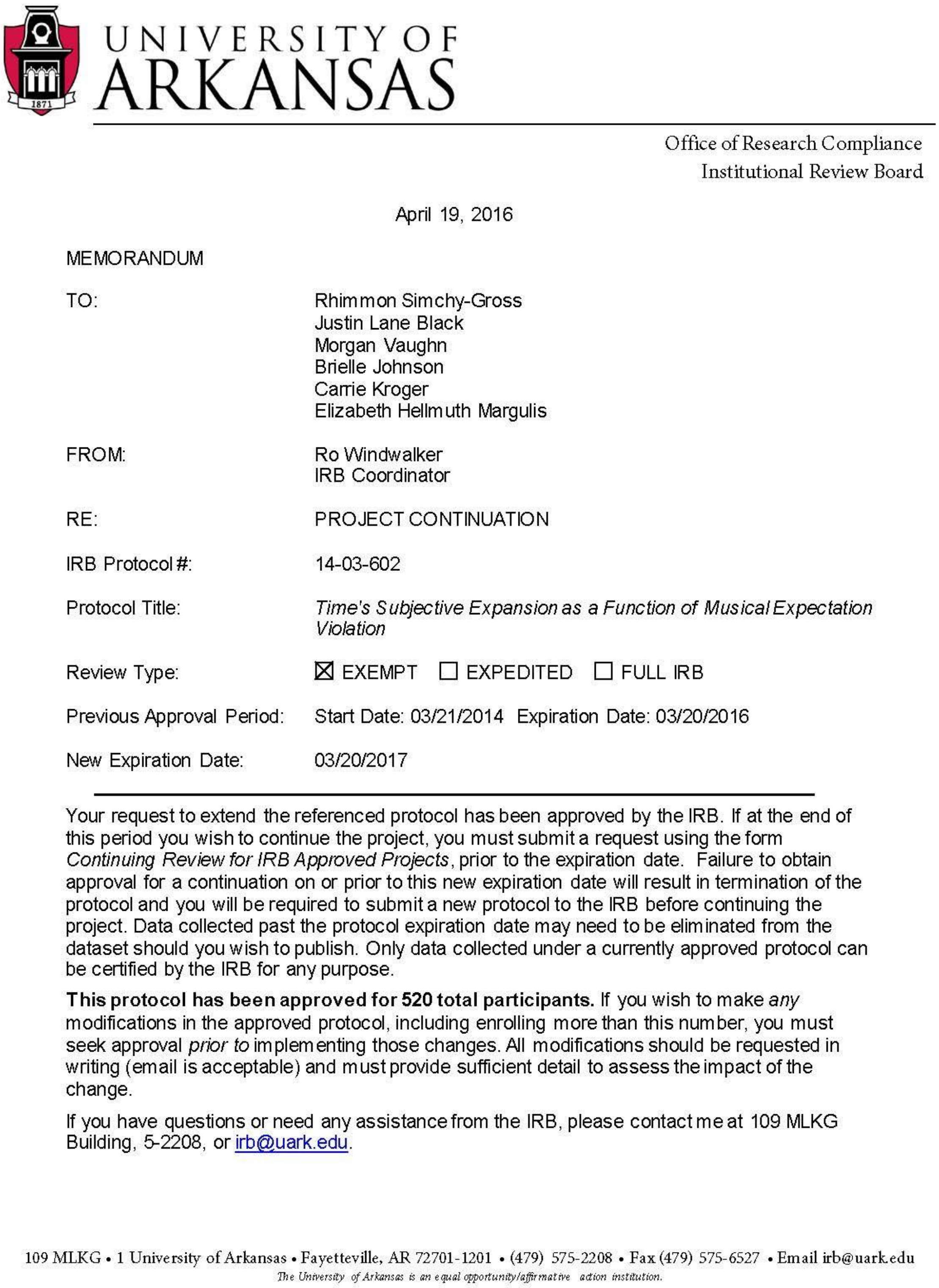


Figure 9. Mean ratio scores (±1 SEM) for the chord sequences that contained oddballs and those that did not as a function of event structure and event familiarity in experiment 2

Appendix

Research Compliance Approval, Experiments 1 and 2



UNIVERSITY OF ARKANSAS

Office of Research Compliance
Institutional Review Board

April 19, 2016

MEMORANDUM

TO:	Rhimmon Simchy-Gross Justin Lane Black Morgan Vaughn Brielle Johnson Carrie Kroger Elizabeth Hellmuth Margulis
FROM:	Ro Windwalker IRB Coordinator
RE:	PROJECT CONTINUATION
IRB Protocol #:	14-03-602
Protocol Title:	*Time's Subjective Expansion as a Function of Musical Expectation Violation*
Review Type:	☒ EXEMPT ☐ EXPEDITED ☐ FULL IRB
Previous Approval Period:	Start Date: 03/21/2014 Expiration Date: 03/20/2016
New Expiration Date:	03/20/2017

Your request to extend the referenced protocol has been approved by the IRB. If at the end of this period you wish to continue the project, you must submit a request using the form *Continuing Review for IRB Approved Projects*, prior to the expiration date. Failure to obtain approval for a continuation on or prior to this new expiration date will result in termination of the protocol and you will be required to submit a new protocol to the IRB before continuing the project. Data collected past the protocol expiration date may need to be eliminated from the dataset should you wish to publish. Only data collected under a currently approved protocol can be certified by the IRB for any purpose.

This protocol has been approved for 520 total participants. If you wish to make *any* modifications in the approved protocol, including enrolling more than this number, you must seek approval *prior to* implementing those changes. All modifications should be requested in writing (email is acceptable) and must provide sufficient detail to assess the impact of the change.

If you have questions or need any assistance from the IRB, please contact me at 109 MLKG Building, 5-2208, or irb@uark.edu.

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