THE INFLUENCE OF FREQUENCY AND INTENSITY PATTERNS
ON THE PERCEPTION OF PITCH

DISSERTATION

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ABSTRACT

Recent work on auditory pitch perception has shown that when listeners hear a sequence of tones increasing or decreasing in frequency, their judgments regarding the pitch of a tone appear to shift in the direction implied by the immediately preceding context sequence. One explanation for these results is that expectations are generated by exposure to a dynamic frequency pattern and as a result listeners make systematic pitch judgment errors specific to continuation of the frequency pattern. The main goal of this study is to determine whether dynamic intensity changes, like dynamic frequency changes, also contribute to pattern-based expectations in listeners. In a series of four experiments, listeners heard context sequences of tones that changed dynamically in frequency and intensity, and judged whether the pitch of a variable final tone (probe) was the same as or different from the immediately preceding tone. Experiment 1 sequences comprised simple monotonically changing frequency and intensity patterns. In Experiment 2, listeners heard longer sequences that implied periodically changing frequency and intensity patterns. And using the same frequency patterns from Experiment 2, Experiment 3 incorporated regularly recurring intensity accents and sequences in Experiment 4 included randomly occurring intensity accents. Results are discussed in terms of hypotheses associated with internalized physical principles, pattern-based expectations, and dimensional congruency.
Dedicated to my parents, who taught me to love learning.
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CHAPTER 1

PITCH, INTENSITY, AND REPRESENTATIONAL MOMENTUM

Introduction

Most sounds listeners encounter on a daily basis come in the form of patterns such as speech and music. These sound patterns are complex and acoustically rich. Music, for instance, is composed of a series of sounds whose frequencies and intensities dynamically change in various ways over time. These changes may be either continuous or discrete and they may or may not be coordinated between the dimensions involved. Nonetheless, surprisingly little research has been undertaken to investigate the joint effects of dynamic frequency and intensity changes on the perception of pitches that comprise a sound pattern.

The goal of this dissertation is to investigate whether judgments about individual elements in such patterns are affected by their dynamic context. Specifically, of interest is how judgments regarding the pitch of a probe tone are influenced by the structure of a dynamic auditory pattern that is composed of tones that vary in both frequency and intensity. In one area of research it has been shown that when listeners hear a sound pattern structured such that tones either increase or decrease in frequency (holding intensity constant), their judgments of a final probe pitch appear to shift in the direction implied by the immediately preceding induction sequence (Freyd, Kelly, & DeKay, 1990; Hubbard, 1995a; Johnston & Jones, in press; Kelly & Freyd, 1987). Specifically, when
the frequency of the probe tone preserved the general structure of the experienced pitch trajectory, listeners were more likely to incorrectly report that the probe tone was the same pitch as the preceding tone (i.e., the final induction sequence tone). Numerous hypotheses have been proposed to explain such observations. The original and most prominent explanation proposes that these errors reflect implicit knowledge of certain invariant physical principles. The internal representation of motion (here in pitch space) is presumably dynamic and analogous to physical laws of motion. As a result, this view correctly predicts that judgments should be systematically distorted in a manner consistent with this knowledge. The term representational momentum (RM) has been used to describe this systematic error shift.

Johnston and Jones (in press) recently presented new data that is consistent with an alternative theory involving pattern-based expectancies. They proposed that listeners generate expectancies regarding the pitch of upcoming tones based on the unfolding structure of the specific pattern to which they are exposed. The data they present are based on longer auditory sequences, structured such that tones implied a periodic pattern in pitch space. They found that listeners’ judgments reflected errors associated with anticipation of the higher-order frequency pattern and did not reflect an automatic extrapolation of the local frequency trajectory. It is the goal of this dissertation to assess these and related hypotheses, along with investigating effects of intensity variations within this paradigm.

Representational Momentum
Visual Representational Momentum

The majority of research on RM has been conducted in the visual domain. Observers in these studies tend to incorrectly remember an event, undergoing real or implied motion in space, as shifted beyond its actual final position. In Freyd and Finke's (1984) initial study investigating this phenomenon observers viewed an induction sequence of three discrete rectangles, presented over time such that successive orientations implied rotational motion. This sequence was followed by a probe rectangle that could have the same orientation as the third rectangle, or be rotated slightly forward or backward along the implied path of rotation. Subjects judged whether the orientation of the probe was the same as or different from the immediately preceding, i.e., the third, rectangle. Results showed that subjects were more likely to respond ‘same’ for probes that were rotated further along the implied direction of rotation, and this effect disappeared when rotation was not implied in a control condition.

Freyd and Finke (1984) hypothesized that the internal representation of motion is analogous to physical laws of motion. In this case the hypothesis involves an analogy to physical momentum. Under this view RM specifically results from a spontaneous and automatic memorial extrapolation that has inertia (Finke, Freyd, & Shyi, 1986). In other words, similar to the motion of a physical object, the memory for a changing sequence is endowed with motion that requires some time to cease. Halting this mental extrapolation requires an opposing internal force, termed cognitive resistance.

More recently, Hubbard (1995b) proposed the environmental invariants hypothesis. This hypothesis expands the original metaphor that was confined to the role of the physical principle of momentum in mental representations. Under Hubbard’s view,
RM reflects implicit knowledge of environmentally invariant physical principles that have been incorporated into a representational system through human evolution and individual experiences. Physical momentum is simply an instance of one of many environmental invariants that may systematically distort memory. Therefore, when one views a moving object (or a series of objects that imply motion), the internal representation of this event is biased towards being consistent with the physical principle of momentum. Hubbard’s research suggests that RM is just one example of this bias. Consistent with his environmental invariants hypothesis is research that suggests that errors reflect physical principles other than momentum (see Hubbard, 1995b). For example, using vertically moving objects of varying sizes Hubbard found a greater shift in errors for probes that followed a large downward moving object, reflecting an analog of weight in the representational system (Hubbard, 1997); similarly, given an object moving in a circular orbit, errors were shifted forward and inward suggesting an internalization of centripetal force (Hubbard, 1996).

**Auditory Representational Momentum**

The majority of research on RM has been conducted in the visual domain (Finke, et al., 1986; Freyd & Finke, 1984; Hubbard, 1995b; Kelly & Freyd, 1987), however evidence for RM has also been found in the auditory domain. A handful of studies show that changes associated with a succession of tones that imply motion result in RM either in real space or in pitch space (Freyd, et al., 1990; Getzmann, Lewald, & Guski, 2004; Hubbard, 1995a; Kelly & Freyd, 1987), result in RM. Under certain conditions listeners’ reports are consistent with a probe being shifted in the direction implied by properties of
the immediately preceding auditory sequence. However the literature at this point is limited. Below are summaries of the findings from four studies.

Kelly and Freyd (1987) were the first to demonstrate that RM occurs in the auditory domain. They conducted a series of studies showing that RM is associated with transformations not related to physical momentum. In Experiment 8, they presented listeners with a sequence of three discrete tones that increased or decreased in frequency, followed by a probe tone that was either the same frequency as the third tone or higher or lower in frequency. Participants judged whether the pitch of the probe was the same as the third tone or different. Kelly and Freyd found that participants were more likely to say ‘same’ to probes that preserved the direction implied by the sequence, thus showing that RM is not restricted to the visual modality.

RM in the auditory domain was further explored in research conducted by Freyd, Kelly, and DeKay (1990) and Hubbard (1995a). The goal of both of these studies was to replicate, in the auditory domain, various circumstances in which RM is found in the visual domain. Similar to vision studies, Freyd, et al. (1990) found the following: 1) RM disappeared when the serial positions of the first and second tones were switched; 2) RM was greater for induction sequences that implied faster versus slower velocities (pitch/time) with velocity manipulated by varying the inter-stimulus intervals (ISI) in the induction sequence; 3) RM was greater when the induction sequence implied acceleration versus a constant velocity or deceleration; 4) when the retention interval (ISI preceding the probe) increased, RM first increased and then decreased as retention intervals lengthened, peaking at 100 ms. Hubbard (1995a) found additional evidence of RM for pitch in the auditory domain. Specifically, RM was observed whether the induction
sequence had actual motion, with pitch glides, or simply implied motion, with discrete tones.

Most recently, a fourth experiment conducted by Getzmann, Lewald, and Guski (2004) can be compared more directly to visual RM studies. Listeners in their study were seated in a dark anechoic chamber facing an array of speakers aligned in the horizontal plane. They heard continuous noise or noise bursts that traveled from right to left or left to right 36°, with four different starting locations and two different velocities. The listeners’ task was to rotate a hand pointer to the position where the sound stopped. Results indicated RM occurred for both continuous noise and noise bursts, paralleling the findings of visual RM in the auditory spatial domain.

In summary, these four experiments indicate that the RM phenomenon occurs in both the visual and auditory domains. Specifically, listeners’ reports are consistent with a probe tone being shifted in the direction implied by properties of the immediately preceding auditory sequence. This is observed when the preceding auditory sequence contains motion or simply implies motion in pitch space or real space.

Representational Momentum and Expectancies

It is important to recognize that, by virtue of the label alone, the term representational momentum (or RM) seems inextricably linked to a theoretical explanation based on internalized physical principles. However, more neutral terms, such as memory shift, displacement, or extrapolation, have also been enlisted to describe these errors (Hubbard, 1995b; Kerzel, 2003; Verfaillie & d'Ydewalle, 1991). A neutral term may be a more appropriate descriptor because emerging research indicates that the
systematic error shifts observed in these studies can be influenced by factors, such as expectancies, that are unrelated to momentum or other physical principles (Freyd & K. T. Jones, 1994; Hubbard & Bharucha, 1998; Johnston & Jones, in press; Reed & Vinson, 1996; Verfaillie & d'Ydewalle, 1991).

Along these lines, an alternative explanation for the RM phenomenon, which involves an apparent extrapolation, is based on expectancy. One kind of expectancy that has been shown to influence performance in these tasks involves conceptual knowledge. In the visual domain, Reed and Vinson (1996) have shown that expectations associated with an object’s identity affect extrapolation. Participants viewed an ambiguous object that they were told was a “rocket” or a “steeple”. Results showed that errors reflected an individual’s knowledge regarding the typical motion of an object. Thus, observers told that the object was a “rocket” were more likely to incorrectly report a probed version of the object’s location as higher than it actually was, as compared to observers who were told that the object was a steeple; this was especially true when the induction sequence implied upward motion.

Similarly, in the auditory domain, Hubbard (1993) experimentally pitted low-level extrapolations against schematic expectations associated with Western music. Listeners heard an induction sequence of three tones that ascended in pitch, and which realized the tonic (I), dominant (V), and octave (VIII) pitch relations of a familiar major scale. In addition, the third tone of the sequence instantiated either a precise octave interval (relative to the first tone) or it was mistuned slightly lower in pitch (flat) or higher in pitch (sharp). This three-tone induction sequence was followed by a probe tone that was slightly higher, lower, or the same frequency as the third tone. Although in other
situations, listeners’ performance might be biased by simple upward pitch extrapolations based on lower-order pattern structure, here this tendency appeared to be over-ridden by their knowledge of Western musical scales. Hubbard found that listeners incorrectly judged higher frequency probe tones as the same as the third tone when the third tone was flat (or an octave, although this error shift was not statistically significant), as would be predicted on the basis of previous RM studies. However, when the third tone was sharp, they incorrectly judged lower probes as being the same pitch as the third tone, demonstrating that errors were shifted in the direction of the true octave interval. Hubbard interpreted these findings to mean that conceptual knowledge about Western tonal music dominated listeners’ expectancies about pitch in this situation.

A second kind of expectancy that has been shown to influence extrapolation is associated with exposure to patterned stimuli. Within the visual RM literature, Hubbard and Bharucha (1988) investigated whether viewing an object with periodic motion would influence extrapolation. In Experiment 4, subjects viewed a target circle that moved horizontally or vertically at a constant velocity and appeared to bounce back and forth within a large square frame. In this experiment, the observed pattern of motion contains both lower-order and higher-order pattern structure. The lower-order pattern is associated with linear horizontal or vertical motion and the higher-order pattern is associated with the overall periodic motion of the entire pattern created when the target changes direction. The target disappeared at one of three locations relative to the nearest wall of the frame: precollision, collision, or postcollision. Subjects used a computer mouse to position the cursor over where they believed the target was when it disappeared. Hubbard and Bharucha found that for precollision and collision vanishing points, errors did not
reflect a simple extrapolation of the current, lower-order, path of motion, instead errors were shifted backwards reflecting anticipation of the future change in direction associated with the higher-order periodic pattern.

Similar to Hubbard and Bharucha’s study with periodic motion, Verfaillie and d'Ydewalle (1991) found that judgment errors are also influenced by sequential patterns that imply periodic motion. Using the basic paradigm of Freyd and Finke (1984), they created a periodic condition in which subjects viewed nine successive presentations of a rectangle whose orientations implied a higher-order rotation in a back-and-forth motion, followed by a probe rectangle. Thus, these sequences contained lower-order pattern structure associated with the local (implied) rotational motion between successive rectangles and higher-order pattern structure associated with the overall (implied) periodic motion of the entire pattern. In conditions where the location of the probe was always at a period boundary (a direction change), i.e., at a point where lower-order and higher-order pattern trajectories differed, Verfaillie and d'Ydewalle made two predictions. One prediction posits a primary role for lower-order structure in that a positive extrapolation may be observed due to the extrapolation of local motion. This result would be consistent with error shifts found with Freyd and Finke’s original shorter sequences that implied a single consistent direction of rotation. Their alternative prediction about performance at this boundary point favors a dominant role for higher-order structure in that either a null extrapolation or a negative extrapolation should emerge at the period boundary because at this point the direction of rotation reverses. Indeed, Verfaille and d’Ydewalle found that extrapolation was eliminated at the boundary point, supporting the higher-order motion hypothesis. They concluded that memory for
the final rectangle’s orientation was influenced by anticipation of the higher-order
periodic pattern, rather than by extrapolation of the local lower-order pattern.

Several other studies have shown that viewing complex patterns leads to
anticipations that the pattern will continue. Freyd and K. T. Jones (1994) had people view
a ball moving through a spiral tube, followed by a probe ball that was in the same
position as the final ball position or positively or negatively displaced. Even though
participants knew that a ball would move in a straight path upon exiting a spiral tube,
errors reflected extrapolation along a spiral path, versus a straight path. Despite
conceptual knowledge of a straight path, as dictated by physics, these errors reflected an
extrapolation of the curved path and thus were consistent with perception of the spiral
pattern. Using more complex stimuli, Verfaillie and Daems (2002) had people view short
animations of human movement, followed by a possible/impossible figure task. The
figures could be completely new body poses or poses that would have resulted if a
previously viewed motion sequence had continued. They found that observers were faster
at identifying possible figures that were primed by the short animations, and they
concluded that short-term anticipation during the animations led to long-term priming.

Evidence of pattern-based expectations has recently been found in the auditory
domain. In a series of pitch judgment experiments, Johnston and Jones (in press)
presented listeners with induction sequences of discrete tones that implied periodically
ascending and descending motion in pitch space, followed by a probe tone. In one
experiment, participants were instructed that they would hear a sequence of 10 to 13
tones followed by a probe tone and that their task was to judge whether the pitch of the
probe tone was the same as or different from the final sequence tone.
Two types of frequency patterns were used in this experiment. An example of the undulating pitch pattern denoted as pattern A is depicted in Figure 1.1. Pattern A begins with a falling frequency pattern and ends with a rising frequency pattern. The mirror image of pattern A, pattern B (also shown in Figure 1.1), undulates in the reverse direction, i.e., the opening tones (2, 3, and 4) were progressively higher in frequency, tones 5, 6, and 7 were lower, tones 8, 9, and 10 were higher, and tones 11, 12, and 13 (when present) were lower. Thus, all sequences had a frequency structure that transpired over two different, but related, time levels. Lower-order structure is associated with the local change in frequency between successive tones that occur every 500 ms. Higher-order structure is associated with the overall implied periodic motion that is marked by period boundaries every 1500 ms. It should also be noted that the temporal structure of these two time levels is very coherent, i.e., regular, with the lower level nested within the higher level. Of special interest is the types of errors that occur at a period boundary (a frequency direction change), where lower-order and higher-order frequency structure differs. Results indicated that listeners appeared to anticipate the higher-order periodic pattern.

The key finding that supports this interpretation involves an interaction of pattern type (A and B) with sequence length (10, 11, 12, and 13). Figure 1.2 presents this interaction. The dependent variable used to assess extrapolation errors is a weighted measure (WM) (Hubbard, 1995a). For each individual the proportion of ‘same’ responses at each level of a probe was weighted by the actual frequency shift in cents, these values were summed and divided by the sum of the proportion of ‘same’ responses. The result is a single number whose sign indicates the direction of error shift, and value is in an index.
of the magnitude of the error shift (larger values indicate greater shift in errors). When this is computed for a probe following any sequence length, a positive WM score reflects ‘same’ responses to higher probes whereas a negative WM score reflects ‘same’ responses to lower probes. Note, however, that a WM score of zero can indicate either accurate performance or an even distribution of errors between higher and lower probes.

\[
WM = \frac{(-70 \times P_{\text{same},-70}) + (-35 \times P_{\text{same},-35}) + (0 \times P_{\text{same},0}) + (35 \times P_{\text{same},35}) + (70 \times P_{\text{same},70})}{\Sigma P_{\text{same},i}}
\]

The results of the Johnston and Jones study were clear cut. When listeners heard pattern A having a length of 10 tones and followed by a probe tone that was slightly higher or lower in frequency than the 10\textsuperscript{th} tone (i.e., at the onset of an ascending frequency trajectory), they were more likely to respond ‘same’ to higher probes than to lower probes, accordingly the average weighted measure was +8.9. This suggests that listeners made anticipatory errors consistent with the upcoming reversal in the frequency trajectory associated with the higher-order periodic pattern. In addition, when listeners heard pattern A with a length of 13 tones followed by a probe tone that was slightly higher or lower in frequency than the 13\textsuperscript{th} tone (i.e., at the onset of a descending frequency trajectory, if the sequence was to continue), they were more likely to respond ‘same’ to lower probes than to higher probes, the average weighted measure was -2.3. The opposite pattern of findings was observed with pattern B, the mirror image of pattern A. These results suggest that listeners made anticipatory errors consistent with an upcoming reversal in the frequency trajectory associated with the higher-order periodic pattern. With complex sequences that implied periodic ascending and descending motion,
listeners’ errors at period boundaries reflected extrapolation of the pattern’s frequency relationships in a direction consistent with the higher-order periodic pattern and inconsistent with the direction of the immediately preceding, i.e., lower-order, frequency trajectory. Finally, in a control experiment where the serial order of the induction sequence tones was randomized, implying no coherent frequency pattern, this effect disappeared.

These results are difficult to explain with the conventional RM hypothesis. This is because the physical momentum hypothesis attributes these systematic error shifts to extrapolation based on internalized physical principles and not to global aspects of serial pattern structure (Finke, et al., 1986; Freyd & Finke, 1984). The RM approach assumes that errors reflect shifts in the memory of a mental representation that mimic the physical principle of momentum. That is, distortions do not occur in real time but in memory. Furthermore, these errors should reflect an automatic extrapolation of the lower-order frequency trajectory, not anticipation of the global, higher-order frequency pattern. Instead, the results are consistent with a pattern-based expectancy hypothesis (Johnston & Jones, in press). According to this hypothesis, exposure to a dynamic auditory pattern generates expectancies regarding the attributes of future events. Given a pattern that is rhythmically simple, attention will be targeted in time to when the next event will occur and what that next event will be, e.g., its pitch. As a result, errors reflect the anticipation that future events will be consistent with continuation of the established pattern.

In summary, three different hypotheses have been proposed to explain RM. The physical momentum hypothesis attributes extrapolation to a memorial representation that has inertia. The environmental invariants hypothesis attributes extrapolation more
generally to an internalization of invariant physical principles, such as momentum, weight, and centripetal force. Finally, a pattern-based expectancy hypothesis posits that exposure to a coherent pattern yields expectancies that the pattern will continue and error shifts reflect this anticipation. All of these approaches have been evaluated by using events that vary along a single dimension, e.g., movement in frequency space. The goal of this dissertation is to evaluate these hypotheses using events that vary along multiple dimensions. Thus, the RM phenomenon is examined with sequences that vary systematically along the dimensions of frequency and intensity. Currently there are no studies investigating this using the RM paradigm. Therefore, the following section reviews other areas of research that have investigated the influence of intensity on pitch perception.

Influence of Intensity on Pitch Perception: Implications for Sequence Perception

Auditory RM studies have shown that a listener’s ability to judge whether two tones are identical or different in pitch is systematically distorted when these tones are preceded by a tone sequence that implies a linear or periodic frequency pattern. These results indicate that pitch perception is influenced by a surrounding auditory context that contains frequency variations. However, commonly experienced auditory patterns, such as speech and music, do not vary simply in frequency. Dynamic intensity variations also occur within auditory patterns and may affect pitch perception. Currently, the influence of intensity on pitch perception has not been investigated within the auditory RM paradigm. However, the influence of intensity on the accuracy of pitch perception has been the subject of research conducted within the domains of psychoacoustics, the
perception of multidimensional stimuli, and perception of dynamic stimuli. This research
can be divided into two groups based on their experimental stimuli. Psychoacoustics and
the perception of multidimensional stimuli approach use isolated steady state tones,
whereas research on perception of dynamic stimuli uses isolated tones that contain
monotonic frequency and/or intensity glides. Findings from these approaches are
discussed subsequently and they provide a basis for predicting how dynamic intensity
patterns within a longer auditory tone sequence will influence pitch perception.

Research with isolated steady state tones

The vast majority of research on auditory pitch perception comes from the field of
psychoacoustics. Traditionally psychoacoustic approaches use stimuli composed of
isolated steady state tones, i.e., rather than sequences of tones. Nevertheless, this research
is relevant to the present project because it has revealed that although the perception of
the pitch of a steady state tone is primarily dependent upon its frequency, it is also
affected by intensity (Fletcher & Munson, 1933; Moore, 2003; Stevens, 1975). Stevens’
(1934; 1975) classic work on the influence of discrete intensity changes on pitch
perception found that increasing intensity changed perceived pitch. When listeners heard
two tones identical in frequency and above 3 kHz, and the intensity of one of the tones
was increased it was incorrectly judged as being higher in pitch than the softer tone.
Given two tones identical in frequency and below 3 kHz, when the intensity of one of the
tones was increased it was incorrectly judged as being lower in pitch than the softer tone.
In a typical task investigating the effect of discrete intensity changes on pitch perception,
listeners match the pitch of two tones by either adjusting the intensity of one of two tones
that differ in frequency, or adjusting the frequency of one of two tones that differ in intensity. Even though replications have found large between and within subject variability (see Cohen, 1961), Stevens’ (1934) results with pure tones have been replicated; listeners will incorrectly report that two such tones, whose frequencies differ by a 1 to 5% change in Hertz, are identical in pitch when they have different intensities (Moore, 2003).

Stevens’ research is a significant contribution to the understanding of pitch perception. These results show that pitch perception is influenced by intensity. Although these studies are based on perception of isolated tone pairs, it is possible that with longer auditory patterns intensity changes may influence pitch perception in a similar fashion. That is, within longer auditory sequences, individual steady state tones with high frequencies may have a higher perceived pitch when the intensity is increased and low frequencies may have a lower perceived pitch when the intensity is increased. This approach will be referred to as the *isolated tone pairs hypothesis*.

In addition to psychoacoustic studies, research on the perception of multidimensional stimuli also uses isolated steady state tones to investigate the influence of intensity on pitch perception. Classic work by Garner (1974) is concerned with determining whether perceptual dimensions, e.g., loudness and pitch, interact with each other or not. Specifically, dimensions are termed integral if, when they co-occur, the dimensions convey a unitary whole (dimensionless). Operationally, this means that considerable effort is required for a listener to selectively attend to aspects of just one of the two dimensions. Conversely, dimensions are separable if, when they co-occur, the dimensional structure of each is directly perceived, indicating that little effort is required
to selectively attend to a single dimension. Garner’s (1974) approach is termed holistic processing, because of the assumption that integral dimensions are perceived as dimensionless, unanalyzable, holistic “blobs”.

Garner proposed a set of converging operations (speeded sorting task, restricted classification task, and dissimilarity scaling) that determine whether two dimensions are separable or integral. When these tasks are applied to the dimensions of pitch and loudness, stimulus items are discrete tones whose frequency and intensity are varied. Because both the dimensions of pitch and loudness are continuous, with values ranging from small to large, a stimulus item is positively correlated when it is high (or low) in both frequency and intensity and it is negatively correlated when it is a high value on one dimension and a low value on the other. With integral dimensions (versus separable dimensions) the following results typically obtain from converging operations: 1) when sorting items on the basis of one dimension, orthogonal variation produces interference and correlated variation produces facilitation as evidenced by reaction time measures, 2) items are grouped according to overall similarity, not shared dimensional values, and 3) similarity judgments conform to a Euclidean distance metric not a city-block metric. Using these converging operations, Grau and Kemler-Nelson (1988) found evidence that pitch and loudness are integral dimensions and that these dimensions influence each other similarly. Therefore, according to this view, a single steady state tone having some frequency and intensity is initially perceived as a dimensionless whole, and only with effort can each dimension be accessed separately.

Melara and colleagues (Melara & Marks, 1990a; Melara & Marks, 1990b; Melara, Marks, & Lesko, 1992; Melara, Marks, & Potts, 1993) have proposed an alternative
account of how multidimensional stimuli are perceived. They hypothesize that perceivers always have immediate and mandatory access to perceptual dimensions. This is termed attribute-level processing, because people are always able to access individual attributes of the dimensions (e.g., a tone’s pitch or loudness). With integral dimensions however, extraction of attributes along one dimension (e.g., pitch) occurs within the context of the other dimension (e.g., loudness). This contextual influence is termed stimulus-level processing. Thus, with integral dimensions, context created by one dimension constrains the experience of attributes in the other dimension. Melara, Marks, and Lesko (1992) were able to provide evidence against Garner’s holistic processing approach with the putatively integral dimensions of pitch and loudness. They found that the type of instructions listeners received, either emphasizing perceiving a sound as a unitary whole or as composed of values along each dimension, dictated whether similarity judgments were consistent with either integral or separable dimensions. They interpreted this to mean that even with these integral dimensions, listeners have immediate access to values along each dimension.

An additional finding by Melara and Marks (1990b) was that how the values on each dimension were manipulated influenced perception. In several experiments, listeners were presented discrete tones and were required to sort them along one dimension (e.g., soft or loud) and ignore the irrelevant dimension (e.g., low and high pitch). They found that positively correlated stimuli (e.g., loud and high pitch) were classified faster than negatively correlated stimuli (e.g., soft and high pitch) in both orthogonal and correlated sorting tasks. They define positively correlated stimuli as congruent because pitch and loudness values are drawn from similar ends of the two dimensions. Likewise, negatively
correlated stimuli are defined as *incongruent* because pitch and loudness values are drawn from opposite ends of the two dimensions. Melara and Marks interpret their results as evidence that listeners are extracting and processing dimension-specific information.

Research on the perception of multidimensional stimuli adds to the evidence that pitch perception is influenced by intensity. However, in general such findings have been based on perceptual judgments of isolated steady state tones; they do not arise from pitch judgments of more naturally occurring dynamic sound patterns. Even so, it seems likely that with longer auditory tone sequences, ones containing frequency and intensity patterns, these dimensions will still be perceived as integral. According to Melara and Marks (1990b), *dimensional congruency* affects the time it takes to classify a tone, with faster classification for congruent than for incongruent tones. Similarly, congruent or incongruent frequency changes and intensity changes within a pattern may have differential effects on pitch judgments within the auditory RM paradigm. For instance, listeners’ pitch judgments may be more accurate with congruent versus incongruent sequences. In addition, error shifts may also differ with congruency. Perhaps, a congruent context sequence will yield more RM, i.e., a greater shift in errors, as compared to an incongruent sequence.

In summary, research from both psychoacoustics and perception of multidimensional stimuli has shown that intensity levels influence the perceived pitch of individual steady state tones. Based on psychoacoustics research, when intensity is increased, high frequency tones may have a higher perceived pitch and low frequency tones may have a lower perceived pitch. Research on the perception of multidimensional stimuli comes from two approaches: 1) Garner suggests that pitch and loudness are
integral dimensions and cannot be perceived separately and 2) Melara proposes that these dimensions can be perceived separately and values along one dimension will be perceived within the context of the other dimension. Regardless of whether the processing of the dimensions of pitch and loudness occurs according to Garner’s traditional holistic processing approach or Melara’s alternative approach, research associated with both views has shown that the perception of pitch is influenced by changes in loudness and vice versa. Most interestingly, Melara and Marks (1990b) found effects of dimensional congruency in speeded orthogonal and correlated sorting tasks. It appears that the relationship between the frequency values and intensity values influences perception, with differential performance for congruent (e.g., loud and high pitch) versus incongruent (e.g., loud and low pitch) stimuli.

Research with dynamic stimuli

More recently, experiments have examined perception of tones that contain dynamic variations in frequency and/or intensity. Unlike research with isolated steady state tones, this experimental approach employs tones that contain dynamic frequency and intensity glides. The goal of these studies is to investigate how dynamic changes along an irrelevant dimension, e.g., loudness, influence a listener’s perception of the attended dimension, e.g., pitch. The frequency and/or intensity glides employed in these experiments are more representative of naturally occurring dynamic sound patterns than the isolated steady state tones used in psychoacoustic and multidimensional perception studies.
Numerous studies by McBeath, Neuhoff and colleagues have investigated the influences of dynamic frequency and intensity changes on the perception of pitch and loudness. One assumption of this approach is that in nature there exists a reliable positive correlation between frequency and intensity (McBeath & Neuhoff, 2002). That is, both the dimensions of pitch and loudness are continuous, containing values ranging from small to large, and changes in these dimensions typically occur together and in the same direction. As a result it is to a listener’s advantage to expect sounds that, for example, increase in frequency to also increase in intensity. This suggests that perception is differentially affected by whether pitch and loudness are positively or negatively correlated. This assumption is in agreement with the findings of Melara and Marks (1990b), where positively correlated, or congruent, stimuli were classified faster than negatively correlated, or incongruent, stimuli. The research using dynamic stimuli investigates this positive correlation using frequency and intensity glides.

McBeath and Neuhoff (2002) examined how continuous intensity changes affect the perceived amount of pitch change. In contrast to research with steady state tones, these stimuli consist of tones that can vary continuously in frequency (constant at 1046 Hz, rising or falling) and continuously in intensity (constant at 77.5 dB, rising, or falling) over a time span of 6 seconds. Participants were instructed to ignore any changes in loudness and to track, in real-time, any changes in pitch by moving a response wheel forward (for rising pitch) and backward (for falling pitch). They found a main effect of frequency, such that rising, constant or falling tone frequency was perceived as rising, constant or falling pitch. More interestingly, they also found a main effect of intensity on pitch judgments. When frequency increased and intensity was constant or increasing
listeners responded that pitch was rising and when frequency decreased and intensity was constant or decreasing listeners responded that pitch was falling. However, reported pitch change differed dramatically when frequency and intensity were negatively correlated. When frequency increased and intensity decreased listeners responses indicated only a small rise in pitch and when frequency decreased and intensity increased listeners incorrectly responded that pitch was rising. Finally, when frequency was held constant, rising, constant or falling intensity was perceived as rising, constant or falling pitch. It seems that listeners’ ability to accurately track pitch change was greatly reduced when frequency and intensity were negatively correlated.

The fact that dynamic changes in intensity appear to systematically affect perceived pitch again suggests a perceptual dependency between pitch and loudness. However, it is most important to observe that the results of McBeath and Neuhoff (2002) are in direct conflict with findings from psychoacoustic experiments using isolated steady state tones. That is, Stevens (1934) found that increasing the intensity of a low frequency tone results in reports of lower perceived pitch, whereas here McBeath and Neuhoff found that with a low frequency tone, increasing the intensity continuously, instead of discretely, results in reports of increased pitch. On the other hand, their results are in agreement with research with multidimensional stimuli. Melara and Marks (1990b), found differential effects of congruency, in that listeners were faster at classifying a congruent tone (e.g., loud/high pitch) versus an incongruent tone (e.g., soft/high pitch). Along these lines, McBeath and Neuhoff’s results suggest that when frequency was held constant, listeners mistakenly perceived pitch changes that were congruent with the experienced intensity change. Although these two approaches employ very different
experimental stimuli and paradigms, both provide converging evidence for a *dimensional interaction hypothesis*. This hypothesis generally predicts that congruency between pitch and loudness values influences perception, and more specifically it predicts that listeners will be more accurate at judging pitch when frequency and intensity are congruent versus incongruent.

A complementary study by Neuhoff, McBeath, and Wanzie (1999), investigated the influence of continuous frequency changes on the perceived amount of change in loudness. In this case, subjects tracked loudness changes, instead of pitch changes. Similar results were found. In this situation where intensity was held constant, rising, constant or falling frequency was perceived as rising, constant or falling loudness. This was also the case in a dichotic listening task, where frequency changes occurred in the ignored ear and intensity changes of a white noise signal occurred in the attended ear. The results from this study and from McBeath and Neuhoff (2002) support the findings associated with perception of multidimensional stimuli, in that the perception of pitch is differentially influenced by congruent and incongruent changes in loudness and vice versa.

Congruency effects have also been found in several studies. In a signal detection task, Scharine (2002) had listeners detect the presence of a target sound that was either rising, falling, or constant in frequency and either rising or falling in intensity. The target could occur in one of two intervals that contained a white noise masker. She found that detection thresholds were lower for congruent targets versus incongruent targets. Neuhoff, Wayand, and Kramer (2002) had people listen to tones that increased or decreased in frequency and increased or decreased in intensity and asked them to rate
“how much the sound changed” on a scale of 1 to 100. They found a congruency effect. Even though the amount of pitch change and loudness change was identical, when pitch and loudness changed in the same direction (congruent) listeners rated these sounds as having a greater amount of change than when pitch and loudness changed in different directions (incongruent).

The work of McBeath, Neuhoff and colleagues using dynamic auditory stimuli (2002; Neuhoff, et al., 2002; Neuhoff, et al., 1999; Scharine, 2003) supports the findings associated with perception of multidimensional stimuli. Using a variety of tasks and dependent measures, both approaches demonstrate that the perception of pitch is influenced by changes in intensity, and vice versa, and both have found evidence for perception being influenced by congruency between frequency and intensity. In contrast to psychoacoustic studies and the isolated tone pairs hypothesis, research with dynamic stimuli has consistently found that, with low frequencies, increasing the intensity continuously results in reports of increased pitch not decreased pitch. McBeath, Neuhoff and colleagues attribute their findings to the continuous nature of their stimuli. Moreover, in contrast to the explanations of both Garner and Melara, they offer an alternative explanation for the interaction of pitch and loudness. They suggest that in nature frequency and intensity are positively correlated and that a bias may exist in the neural structure to exploit this. As a result, listeners expect that a dynamic sound will increase (or decrease) similarly in both dimensions.

Summary
In order to devise predictions regarding how pitch perception will be influenced by the dynamic frequency and intensity patterns employed in this study, research from both the RM literature and from several different domains that study how intensity influences pitch perception has been reviewed. Research on auditory RM has addressed how lower-order and higher-order frequency patterns, but not intensity patterns, influence pitch perception. From this literature both the environmental invariants hypothesis, which focuses on the internalization of physical principles, and the pattern-based expectancy hypothesis, which focuses on expectancies generated by pattern structure, are relevant. Research from many domains has addressed how intensity influences pitch perception, however these studies typically use isolated tones as stimuli instead of longer dynamic tone patterns. The isolated tone pairs hypothesis is based on Stevens (1934) finding that high frequency tones are perceived as higher in pitch when the intensity is increased and low frequency tones are perceived as lower in pitch when the intensity is increased. Finally, the dimensional interaction hypothesis refers to the converging evidence that in a range of tasks performance can be differentially affected by whether frequency and intensity are positively correlated, i.e., congruent, or negatively correlated, i.e., incongruent. These hypotheses, and their relationship to the stimuli used in this study, are discussed in greater detail in the following chapter.
Figure 1.1. Schematic of the 13 tone, pattern A and pattern B induction sequences from Experiment 3 of Johnston and Jones (in press). Each induction sequence is followed by the to-be-judged probe tone (hatched circle) that can vary in frequency.
Figure 1.2. Weighted measures for each frequency pattern (A and B) as a function of length from Experiment 3 of Johnston and Jones (in press).
CHAPTER 2
INTRODUCTION TO CURRENT STUDIES

The problem addressed in this research concerns ways in which pitch perception may be influenced by a serial context of dynamically changing frequency and intensity patterns. This is a situation that closely resembles structural changes found in auditory patterns of speech and music. Although various approaches have studied perception of multidimensional auditory stimuli, most of this research has investigated the influence of intensity on pitch perception with isolated tones. It is also the case that the influence of intensity on pitch perception has not been addressed in research using sequences of tones, as seen in the representational momentum (RM) literature, for instance. Numerous RM studies have shown that expectancies formed by exposure to the structure of a visual or auditory pattern influence how upcoming items are perceived (Freyd & Jones, 1994; Hubbard & Bharucha, 1988; Johnston & Jones, in press; Verfaillie & Daems, 2002; Verfaillie & d'Ydewalle, 1991). The main goal of this study is to determine whether dynamic intensity changes, like dynamic frequency changes, also contribute to pattern-based expectations in listeners.

The current research considers whether the frequency and intensity structure of an auditory pattern, comprising a series of discrete tones, influences pitch judgments. The types of pitch judgment errors that are observed may provide evidence that expectations are generated based on dynamic frequency and intensity patterns within an auditory
sequence. Following a preliminary rating experiment, four experiments test hypotheses regarding how intensity variations within the induction sequence influence pitch discrimination. In these experiments listeners judge the pitch of a probe tone that is preceded by an induction sequence of tones that vary in frequency and intensity. In the induction sequence, tones discretely increase and/or decrease in frequency by a fixed change (in cents), implying increasing and decreasing motion in pitch space; simultaneously these tones can also increase and/or decrease in intensity by a fixed change (in decibels), implying increasing and decreasing loudness. Of primary interest is the influence that intensity variations in the induction sequence may exert on pitch discrimination, with specific results lending support to one of four possible hypotheses.

Four hypotheses

Four hypotheses, outlined in Chapter 1, are presented in Table 2.1. These approaches provide predictions for two different dependent measures used in the current study. First, error shifts, or weighted measures (WMs), reflect a listener’s bias toward responding ‘same’ to higher or lower probes. The sign of the WM indicates the direction of error shift and the value of the WM is an index of the magnitude of an error shift. Second, overall accuracy is indexed by proportion correct (PC). These two measures are both useful because WMs alone do not provide sufficient information about accuracy. Specifically, small WMs, close to zero, are ambiguous because they can indicate either very accurate performance or they can reflect that errors are evenly distributed between higher and lower probes. Analyses of PC in conjunction with WMs allow this distinction to be made.
The first two hypotheses presented in Table 2.1 derive from the research on RM. Hubbard’s (1995b) *environmental invariants hypothesis*, which is a generalization of Freyd’s physical momentum metaphor (Finke, Freyd & Shyi, 1986; Freyd & Finke, 1984), proposes that the mental representation of an object that implies motion has properties similar to a physical object with momentum (i.e., the product of mass and velocity). In the auditory domain, pitch velocity may be described in terms of a ratio between pitch distance and time. Furthermore, it might be argued, from this perspective, that intensity is analogous to mass. This seems like a logical translation of the environmental invariants hypothesis to the auditory domain. [Error shifts associated with mass, or weight, have been found in the visual domain. Hubbard (1997) varied size of objects, as an analogy to mass, and found that increasing object size/mass influenced judgment errors.] If these analogies have merit, then Hubbard’s environmental invariants hypothesis predicts that as intensity (or “mass”) increases, the momentum induced by the tone sequence likewise increases, resulting in increased magnitude of extrapolation, or error shifts. In turn, as intensity (or “mass”) decreases, momentum decreases, resulting in decreased magnitude of extrapolation. [In addition, momentum should be greater for sequences composed of tones at a constant high intensity versus a constant low intensity.] Thus, regardless of whether frequency is increasing or decreasing the absolute magnitude of error shifts (WMs) and hence the effects on pitch judgments should be greater with greater intensity. Finally, although this hypothesis is specific with regard to how errors will be shifted (WMs) it makes no predictions regarding how these frequency and intensity patterns will affect accuracy.
An alternative view from the auditory extrapolation literature is Johnston and Jones’ (in press) pattern-based expectancy hypothesis. This approach suggests that error shifts reflect expectations regarding upcoming events that are based on the event structure of the experienced pattern and not on an internalization of invariant physical principles. At this point, the only types of patterns that have been investigated by this approach are frequency patterns that are rhythmically simple. However, this hypothesis applies generally to patterning along any dimension of change. It is possible that the dynamic intensity changes employed in these experiments will be heard as loudness patterns and, likewise, may contribute in some way to the development of pattern-based expectations in listeners, even though intensity manipulations are irrelevant in these tasks where people presumably must attend to probe frequency (Yantis & Egeth, 1999). Nonetheless, this hypothesis does not explicitly address how patterns within different continuously changing dimensions combine or interact to affect performance in a pitch judgment task. Therefore, this hypothesis simply predicts that errors will be shifted (WMs) in the direction implied by the overall frequency pattern. As with the environmental invariants hypothesis, this hypothesis makes no predictions regarding how either frequency or intensity patterns will affect accuracy.

The final two hypotheses do address the interaction of pitch with intensity. Both of these hypotheses derive from research which uses isolated tones to investigate the influence of intensity on pitch perception. Stevens’ work (1934) which leads to the isolated tone pairs hypothesis, implies that with low, versus high, intensities listeners should be more accurate (high PC) at judging the pitch of a probe tone. In addition, with greater intensities errors in pitch judgments may be shifted (WMs) toward lower probes.
Note that these predictions are based only on how listeners will judge an isolated probe tone; in particular, this hypothesis does not predict differences in pitch judgments due to an auditory context that precedes a to-be-judged probe. Essentially, listeners should generally be very accurate at judging the probe tone regardless of the preceding serial context.

Finally, the dimensional interaction hypothesis is based on a confluence of findings from research with multidimensional stimuli and dynamic auditory glides. In summary, this evidence suggests that the perceptual dimensions of pitch and loudness interact (Grau & Kemler-Nelson, 1988) and that congruency between the values on these dimensions also influences perception (Melara & Marks, 1990b; Neuhoff, Wayand, & Kramer, 2002; Scharine, 2002). Based on listeners’ performance in speeded sorting tasks and pitch tracking tasks, it can be predicted that listeners in the current study will likely be more accurate (PC) at making pitch judgments with congruent versus incongruent probe tones.

Extensions of the construct of dimensional congruency to serial patterns seems especially important because various co-variations of frequency and intensity abound in our environment. However, research on dimensional congruence has been restricted largely to reliance on isolated tones or tonal glides. Due to this restriction, this research does not address how values along a given dimension order in real patterns found in speech and music. Therefore, this hypothesis cannot predict how congruency will affect the direction and magnitude of error shifts (WMs) because it considers dimensions in the abstract and not as a basis for creating serial pattern structure. However, a straightforward adaptation of the dimensional congruency findings to serial tone patterns can be made,
given some additional assumptions. Most importantly, assumptions regarding time and
temporal ordering of dimensional values are important to consider. If time is included as
a third dimension then it is possible to determine whether frequency and intensity are
positively or negatively correlated over time. As a sequence of tones unfolds in time the
frequency and intensity values of each successive tone can increase (or decrease) together
to form a congruent monotonic sequence. Conversely, the values of each successive tone
can uniformly increase within one dimension while similarly decreasing along the other
dimension to form an incongruent monotonic sequence. Therefore, through this
adaptation it is logical to predict that dimensional congruency effects can be generalized
to the longer auditory sequences that are employed in the current research. Given
McBeath and Neuhoff’s hypothesis that in nature frequency and intensity are positively
correlated and that a bias exists to exploit this structure, it is possible that congruence
within the induction sequences employed in the current experiments will lead to
systematic errors that reflect continuation of the linear frequency trajectory and that these
shifts may be greater when pitch and loudness changes are congruent (positively
correlated) versus incongruent (negatively correlated).

Research goals

The main goal of this study is to determine how different intensity patterns within
a dynamic frequency pattern affect pitch judgments of a subsequent probe tone. The
intensity patterns employed here include continuous increments that imply linear or
periodic loudness patterns (Experiments 1 and 2) and intensity accent patterns that are
temporally regular or irregular (Experiments 3 and 4). Intensity variations are irrelevant
in all four experiments because listeners are simply required to evaluate pitch. However, because frequency and intensity are integral dimensions (Grau & Kemler-Nelson, 1988), it is unlikely that intensity variations will have no influence on pitch judgments. Thus, a series of four experiments addresses this issue and test the hypotheses detailed above. Predictions from these hypotheses are summarized in Table 2.1 and each will be addressed within the context of forthcoming experiments.

Experiment 1 has two goals. First, it aims to duplicate the findings in the auditory RM literature using simple monotonic induction sequences that contain no intensity changes. A second goal involves investigating how adding intensity changes to simple frequency patterns affects pitch judgments in the auditory RM paradigm. This experiment simultaneously tests explicit predictions, involving either WM and/or PC, from all four hypotheses: environmental invariants, pattern-based expectancy, isolated tone pairs, and dimensional interaction. In Experiment 1 participants hear sequences of four tones that imply increasing or decreasing frequency while also implying increasing, decreasing, or constant intensity. Of interest is how pitch judgments, of a subsequent probe tone, are influenced by these intensity variations. In general, errors should be shifted in the direction consistent with continuation of the frequency trajectory; however, the direction or magnitude of error shifts may be modulated by the intensity pattern in a manner consistent with the predictions of one of the four hypotheses.

The goals of Experiment 2 are twofold. First, it aims to replicate the findings of Johnston and Jones (in press). They found that with tone sequences that implied a higher-order periodic frequency pattern, listeners’ errors reflected a sensitivity to the higher-order periodic pattern and not to the immediately preceding, i.e., lower-order, frequency
trajectory. The second goal of Experiment 2 is to investigate whether pitch judgments about probes following such patterns are also influenced by the addition of coordinated intensity patterns. In this experiment, listeners hear induction sequences that imply periodic increasing and decreasing motion in pitch space plus increasing and decreasing loudness, thus lower-order and higher-order frequency and intensity structure is manipulated. The experiment tests predictions from the pattern-based expectancy hypothesis and other hypotheses that are not ruled out by the outcome of Experiment 1. The question of inherent interest in Experiment 2 concerns whether or not listeners’ errors still reflect a sensitivity to the higher-order periodic pattern and whether or not the error shifts are modulated by whether the intensity pattern is congruent or incongruent with the frequency pattern.

Experiments 3 and 4 build on Experiment 2. The goal of these experiments is to follow up on the pattern-based expectancy hypothesis by attempting to manipulate, through intensity accents, the level of pattern structure to which listeners are likely to attend. Both Experiments 3 and 4 use the same frequency patterns from Experiment 2. However, instead of continuous intensity increments, intensity accents occur either at regular time intervals associated with period boundaries (Experiment 3) or randomly throughout a sequence (Experiment 4). As a result, the sequences in Experiment 3 are rhythmically simple, with the temporally regular intensity accents forming a coherent pattern. It is possible that these coherent intensity accent patterns will reinforce the periodic higher-order frequency pattern, yielding error shifts that are similar to results from Experiment 2. Conversely, the sequences in Experiment 4 are not rhythmically simple. The intensity accents are not evenly spaced in time and are they are
unpredictable, forming a relatively incoherent pattern. It is possible that these temporally irregular intensity accent patterns will be relatively disruptive. If so, this incoherence may force listeners to focus mainly on low-level frequency structure (Jones & Boltz, 1989). Another possibility is that when intensity accents occur at random locations they will be easier to ignore, as these manipulations are not task relevant.

Summary

The overall goal of this research is to investigate how the perceived pitch of a single (probe) tone is influenced by a preceding serial context of dynamically changing frequency and intensity patterns. To this end, in four experiments listeners judge the pitch of a probe tone that is preceded by an induction sequence of tones that imply linear or periodic motion in pitch space and in loudness. Of primary interest is the influence that intensity variations in the induction sequence may exert on pitch judgments errors, with specific results lending support to one of four possible hypotheses: environmental invariants, pattern-based expectancy, isolated tone pairs, and dimensional interaction. In the following four chapters, these predictions are tested.
<table>
<thead>
<tr>
<th>Hypothesis</th>
<th>Predictions regarding error shifts and magnitudes (WM)</th>
<th>Predictions regarding accuracy (PC)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Environmental</strong></td>
<td>• Shift in the direction consistent with extrapolation of the preceding linear frequency trajectory</td>
<td>• none</td>
</tr>
<tr>
<td>Invariants</td>
<td>• Greater absolute shift with high intensity versus low intensity</td>
<td></td>
</tr>
<tr>
<td><strong>Pattern-based</strong></td>
<td>• Shift in a direction consistent with continuation of the overall pattern</td>
<td>• none</td>
</tr>
<tr>
<td>Expectancy</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Isolated Tone</strong></td>
<td>• Shift toward lower perceived pitch with high intensity</td>
<td>• More accurate with low, versus high, intensity probes</td>
</tr>
<tr>
<td>Pairs</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Dimensional</strong></td>
<td>• Differential effect of congruency between dimensions on shift magnitude and/or direction</td>
<td>• More accurate with congruent versus incongruent probes</td>
</tr>
<tr>
<td>Interaction</td>
<td></td>
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</tbody>
</table>

Table 2.1. Four proposed hypotheses and their predictions regarding how frequency and intensity patterns will influence pitch judgments of a subsequent probe tone, as evidenced by error shifts (WMs) and overall accuracy (PC).
CHAPTER 3

MONOTONIC INTENSITY AND FREQUENCY PATTERNS

The literature on auditory representational momentum (RM) has shown that judgments regarding the pitch of a probe tone, preceded by an induction sequence of discrete tones that increase or decrease in frequency, yield specific types of errors (Freyd, Kelly, & DeKay, 1990; Hubbard, 1995a; Kelly & Freyd, 1987). However, no studies have examined the effect of systematic changes in intensity on pitch judgments using this paradigm. It is the goal of this dissertation to determine whether adding intensity changes to induction sequences will also contribute to pitch judgment errors.

Accordingly, induction sequences used in Experiment 1 comprise sequences of discrete tones that uniformly increase or decrease in frequency by a fixed change in cents (a logarithmic scale), implying a simple increasing or decreasing movement through pitch space. Similarly monotonic increases or decreases in intensity are introduced by a fixed change in decibels (a logarithmic scale) to imply uniformly increasing or decreasing loudness. Of interest is whether adding intensity changes to these simple frequency patterns will affect pitch judgments of a subsequent probe tone. In addition, the environmental invariants, pattern-based expectancy, isolated tone pairs, and dimensional interaction hypotheses will be evaluated by comparing their predictions with observed error patterns.
However, before the sequences used in Experiment 1 could be created, it was necessary to determine the size of the intensity change that should be used to imply perceptually equivalent motion within the dimensions of pitch and loudness. It is imperative that changes in pitch are perceptually similar to changes in loudness. Specifically, if the changes in loudness are smaller than the changes in pitch, loudness manipulations may be ineffective. Conversely, if loudness changes are much larger than the pitch changes, loudness manipulations may overwhelm the pitch judgment task. Therefore, a preliminary rating study was conducted in order to determine changes in pitch and loudness that are judged to be perceptually equivalent.

Rating Experiment

All of the experiments in this dissertation employ auditory sequences composed of discrete tones and discrete pitch changes between tones. Thus, the change in frequency between adjacent tones is fixed at 225 cents (c), where 1200 c equals one octave. It is the goal of this rating experiment to determine a change in loudness that is perceptually equivalent to this 225 c change in pitch. On average a 100 c pitch change between two tones is easily discriminated. The smallest usable pitch interval is 100 c in many musical cultures, and due to categorical perception smaller pitch variations are perceptually irrelevant for melodic information (Burns, 1999). Thus, the pitch difference of 50 c is a generous just noticeable difference (jnd), for musically untrained listeners. With a jnd of 50 c, the 225 c change employed in these experiments is equivalent to 4.5 jnds. The aim of this study is to select an intensity change (4.5 jnds) that is roughly equivalent to the subjective magnitude of pitch changes in use. The intensity change that corresponds to
just noticing an intensity difference between two pure tones is roughly one decibel (Moore, 2003). Arguably, therefore a 4.5 intensity jnd, or 4.5 decibels (dB), may reflect an intensity change that is approximately equivalent, perceptually, to the 225 c frequency change.

The goal of the rating experiment is to ascertain whether the fixed dB change (4.5 dB), proposed for use in Experiment 1, is indeed perceptually equivalent to the fixed frequency change (225 c). In this cross-dimensional rating task, listeners judge the similarity between a fixed frequency change, 225 c, and multiple intensity changes. The values of 1.5 dB, 3 dB, 4.5 dB, and 6 dB were chosen as intensity changes because they provide a range of intensity changes that includes 4.5 dB.

Methodology

Subjects. Twenty undergraduate students with normal hearing and fewer than ten years of formal musical training (mean = 3 years) participated in this experiment in exchange for credit in the introductory psychology course at The Ohio State University. The data from one participant was discarded because s/he consistently gave all sequences the same rating of “not similar”.

Apparatus. Stimuli were generated with MIDILAB Version 6.0 software (Todd, Boltz, & Jones, 1989) on a 486 IBM PC-compatible computer interfaced with a Yamaha TG100 Tone Generator (ocarina voice¹), and presented through Beyerdynamic DT 770 headphones. Using a Gen Rad Model 1982 Sound Level Meter (A weighting) with a 1

¹ Due to equipment constraints, ocarina voice instead of sine wave was used for these sequences. However, frequency spectrums revealed that the ocarina and sine wave voices are comparable.
inch microphone and a flat plate coupler, the dB output from one headphone was measured in order to determine the MIDILAB volume settings needed to produce the desired intensities for each frequency.

Sound patterns were presented binaurally through Beyerdynamic DT 770 headphones to listeners seated in separate cubicles in a sound attenuated room. To respond, listeners pressed one of seven buttons (labeled with the numbers 1 through 7) mounted on MIDILAB response panels. Responses were automatically recorded and stored as MIDILAB files.

Stimuli. Stimuli were pairs of four tone sequences comprising a standard followed by a comparison sequence. An example sequence is diagrammed in Figure 3.1. The standard varied systematically in frequency but not in intensity; the comparison varied systematically in intensity but not in frequency. All standard sequences were constant in intensity (70 dB) and either increased or decreased in frequency by 225 c. Standard sequences were composed from three sets of tones described as low [D₅ (587 Hz), E₅ + 25 c (669 Hz), G-flat₅ + 50 c (764 Hz), and A-flat₅ + 75 c (868 Hz)], mid [E₅ + 25 c (669 Hz), G-flat₅ + 50 c (764 Hz), A-flat₅ + 75 c (868 Hz), and B₅ (988 Hz)], or high [G-flat₅ + 50 c (764 Hz), A-flat₅ + 75 c (868 Hz), B₅ (988 Hz), and D-flat₆ + 25 c (1125 Hz)] frequency ranges, as seen in Table 3.1. Increasing frequency standards contained the same tones as decreasing frequency standards, however the serial order of the tones was reversed. The total frequency range from 587 to 1125 Hz is a relatively flat range on Fletcher-Munson equal loudness contours (Fletcher & Munson, 1933).

All comparison sequences were identical in frequency and either increased or decreased in intensity by a fixed dB change (taking on one of four values). The frequency
of the tones in the comparison was the same as the frequency of the 1\textsuperscript{st}, 2\textsuperscript{nd}, 3\textsuperscript{rd}, or 4\textsuperscript{th} tone in the immediately preceding standard sequence. Standard sequences that increased in frequency were always followed by a comparison sequence that increased in intensity and standard sequences that decreased in frequency were always followed by a comparison sequence that decreased in intensity. In addition, regardless of the change in intensity, all increasing intensity comparison sequences had the same final intensity level of 79 dB and all decreasing intensity comparison sequences had the same final intensity level of 61 dB. Table 3.2 shows the dB values used for each comparison sequence tone as a function of intensity change.

Tones within the standard and comparison sequences had durations of 250 ms and inter-onset time intervals (IOIs) of 500 ms. The IOI between the last tone of the standard and the first tone of the comparison was equal to 1500 ms, this temporally segregated the two sequences and preserved the isochronous rate established by the standard sequence (500 ms IOI x 3 = 1500 ms).

\textit{Design.} Direction of the standard sequence, increasing frequency versus decreasing frequency, served as a between subjects variable. Within subjects variables included frequency range (low, mid, and high), comparison sequence frequency (a frequency identical to the 1\textsuperscript{st}, 2\textsuperscript{nd}, 3\textsuperscript{rd}, or 4\textsuperscript{th} tone in the standard sequence), and comparison sequence intensity change (a fixed intensity change between tones equal to 1.5 dB, 3 dB, 4.5 dB, or 6 dB). This resulted in a 2 x (3 x 4 x 4) mixed factorial design, with two standard directions, three frequency ranges, four comparison sequence frequencies, and four fixed intensity changes, yielding in a total of 96 unique standard-comparison sequences. To reiterate, the four different levels of the intensity change
variable distinguish, respectively, four different monotone sequences all with a fixed change in intensity between successive tones.

Procedure. Participants were randomly assigned into an increasing standard direction group (n = 11) or a decreasing standard direction group (n = 8). Each trial involved a standard followed by a comparison sequence, as shown in Figure 3.1. This is a cross-dimensional rating task in which listeners judge whether the standard and comparison sequences have a similar amount of change (Marks, 1989). Participants were told that on each trial they would hear a four-tone sequence that changes in pitch followed by a four-tone sequence that changes in loudness and their task is to rate how similar the amount of change is between the two sequences on a scale of 1 to 7, where 1 is “not similar” and 7 is “very similar amount of change”. They were instructed to use the entire rating scale and to decide on the number value that best describes the degree of similarity judged to obtain between the standard and comparison sequences and to push the button that corresponds to that number.

Listeners in each standard direction group received 16 practice trials, followed by 4 blocks of 48 trials each. Presentation of sequences was randomized, with all 48 patterns associated with the specific standard direction group occurring within each block, thus listeners heard each sequence four times. At the conclusion of the experiment, participants filled out a questionnaire regarding their musical experience and their impressions of the task.

Results
To estimate which intensity change value was rated as most similar to the 225 c frequency change presented in the standard sequences, the number of times a “similar” rating was given (5, 6, and 7) was divided by the total number of responses (48) for each level of intensity change. Table 3.3 presents the proportion of “similar amount of change” responses averaged over all participants. Overall the highest proportion of “similar amount of change” responses were given to the 4.5 dB intensity change (.597), followed by 6 dB (.531), 3 dB (.523), and 1.5 dB (.351). In addition, listeners gave the highest similarity rating (7) most often to the 4.5 dB intensity change (209 times), followed by 6 dB (173 times), 3 dB (143 times), and 1.5 dB (77 times). These results along with research in the literature (Burns, 1999; Moore, 2003) justify using a fixed 4.5 dB change in Experiment 1 as a perceptual equivalent to the fixed frequency change (225 c).

**Experiment 1: Monotonic Intensity and Frequency Patterns**

The auditory RM paradigm employs patterns of discrete tones that imply motion in pitch space. When listeners hear tone sequences that monotonically increase or decrease in frequency, errors in judging the pitch of a final probe tone are shifted in the direction implied by the sequence (Freyd, et al., 1990; Hubbard, 1995a; Kelly & Freyd, 1987). The main goal of Experiment 1 is to extend these findings by investigating whether or not the addition of intensity changes to these patterns impacts pitch judgments. Accordingly, the tone patterns in this experiment change linearly in frequency and intensity, as shown in Figure 3.2. However, frequency and intensity directions are crossed in this design to create sequences in which the monotonic arrangements of values
along these dimensions are either positively (congruent) or negatively (incongruent) correlated. This is shown in Table 3.4.

Predictions regarding shifts in pitch judgment errors in this experiment come from four different hypotheses: environmental invariants, pattern-based expectancy, isolated tone pairs, and dimensional interaction. The primary measure used to evaluate these hypotheses is a weighted measure (WM) which indexes the direction and magnitude of error shifts. However, supplementary analyses of overall accuracy (PC) are also informative, particularly for the isolated tone pairs and dimensional interaction hypotheses. These predictions are graphically displayed in Figure 3.3. In each panel the direction and magnitude of error shifts (WMs) are plotted for the increasing and decreasing frequency patterns as a function of the four intensity patterns (constant loud, increasing, decreasing, and constant soft). Positive WMs indicate that listeners are more likely to respond ‘same’ to high frequency probe tones and negative WMs indicate that listeners are more likely to respond ‘same’ to low frequency probe tones.

Consider first the *environmental invariants hypothesis*. Predictions are depicted in Panel A of Figure 3.3. This hypothesis attributes error shifts to an internal dynamic mental representation that has properties analogous to physical momentum (Hubbard, 1995b). Pitch velocity is associated with the change in frequency and likewise listeners will be likely to say ‘same’ more to higher probes for increasing frequency sequences and lower probes for decreasing frequency sequences. Moreover, if intensity is considered analogous to mass, then greater intensity (increasing and constant loud conditions) should increase momentum and in turn increase the absolute magnitude of error shifts. Conversely, less intensity (decreasing and constant soft conditions) should decrease
momentum and in turn decrease the absolute magnitude of error shifts. Therefore, this hypothesis predicts that the direction of WMs will reflect a linear extrapolation of the frequency pattern. That is, positive WMs for increasing frequency and negative WMs for decreasing frequency. In addition, the magnitude of WMs should be larger for both constant loud and increasing intensity and smaller for decreasing and constant soft intensity. Finally, this hypothesis makes no predictions regarding how these frequency and intensity patterns will affect accuracy.

Second, the pattern-based expectancy hypothesis generates predictions that appear in Panel B of Figure 3.3. This approach also predicts that error shifts will be consistent with the experienced monotonically increasing or decreasing frequency pattern. This hypothesis posits that patterning along any dimension of change should influence expectations regarding upcoming events. However, it does not explicitly predict how co-occurring intensity changes and frequency changes will interact to influence pitch judgments. Therefore, this hypothesis simply predicts a main effect of frequency pattern, with positive WMs for increasing frequency sequences and negative WMs for decreasing frequency sequences. Similar to the environmental invariants hypothesis, this hypothesis makes no predictions regarding how these frequency and intensity patterns will affect accuracy.

Third, predictions from the isolated tone pairs hypothesis appear in Panel C of Figure 3.3. Research by Stevens (1934) with steady state tones below 3 kHz, suggests that increasing intensity yields decreased perceived pitch. It is possible that intensity manipulations will have a similar effect on pitch perception with the longer auditory sequences of Experiment 1. If this obtains, listeners should be very accurate with
decreasing and soft intensity conditions, i.e., high PC and WMs near zero, and with increasing and loud intensity conditions accuracy should decrease and error shifts should reflect bias toward lower probes.

Finally, predictions from the *dimensional interaction hypothesis* appear in Panel D of Figure 3.3. Under this approach, dimensional congruency findings have been adapted to accommodate issues of pattern structure, as discussed in Chapter 2. This hypothesis generally predicts that pitch judgments should differ according to whether frequency and intensity are positively correlated over serial context, i.e., congruent, or negatively correlated over serial context, i.e., incongruent. It is possible that listeners will be biased toward probe tones that are shifted in a direction that is consistent with continuation of congruent (positively correlated) linear changes present in a sequence; conversely, this bias could decrease when the linear changes are incongruent (negatively correlated). Predictions that flow from this interpretation of the dimensional interaction hypothesis are shown in Panel D of Figure 3.3; these indicate that the direction of error shifts (WMs) are consistent with extrapolation of the linear frequency trajectory and the magnitude of errors is greater for congruent versus incongruent sequences. In addition, this approach predicts greater accuracy overall (high PC) for probe tones that are congruent, i.e., high pitch and loud, as compared to incongruent probe tones.

Experiment 1 is divided into two parts. In Experiment 1A induction sequences are simple linearly increasing or decreasing frequency patterns that contain no intensity variations. The goal of this experiment is to replicate the findings in the auditory RM literature. In Experiment 1B induction sequences are the same linearly increasing or
decreasing frequency patterns however intensity is also manipulated. Each sequence will either increase or decrease in loudness or be constantly loud or soft.

Methodology

Subjects. Sixty-four undergraduate students with normal hearing and fewer than ten years of formal musical training (mean = 2 years) participated in this experiment in exchange for credit in the introductory psychology course at The Ohio State University. The data from four participants were discarded because they responded to fewer than 80% of trials.

Apparatus. All equipment used was identical to the rating experiment.

Stimuli. All patterns were composed of an induction sequence of four tones that increased or decreased in frequency, followed by a to-be-judged probe tone. Adjacent tones in the induction sequences were separated in frequency by 225 c, and their values corresponded to the low, mid, or high frequency ranges used in the rating experiment (see Table 3.1). Increasing frequency sequences contained the same tones as decreasing frequency sequences, however the serial order of the tones was reversed. Tones within each sequence were 250 ms in duration and inter-onset time intervals were 500 ms.

In Experiment 1A, intensity was constant at an intermediate level of 70 dB for all sequences. In Experiment 1B, induction sequences increased in intensity (Figure 3.2 Panel A), decreased in intensity (Figure 3.2 Panel B), or remained constantly soft (65.5 dB) or loud (79 dB) (Figure 3.2 Panel C). Adjacent tones in the increasing and decreasing intensity sequences were separated in intensity by 4.5 dB. The dB values of the four induction sequence tones in an increasing intensity pattern were 65.5, 70, 74.5, and 79
dB. Tones in decreasing intensity patterns used the same dB values but in the reverse order.

Following each induction sequence, in Experiments 1A and 1B, was the to-be-judged probe tone. The probe was 250 ms in duration, had the same intensity as the last tone in the induction sequence, and equally often its frequency was the same as the final tone in the induction sequence, lower by 70 c, lower by 35 c, higher by 35 c, or higher by 70 c.

Design. The design of Experiment 1 is diagrammed in Table 3.4, where the solid arrows symbolize frequency direction and dashed arrows symbolize intensity direction. Note that, in Experiment 1B, congruent patterns are those where arrows associated with both frequency and intensity end at the same high or low point, whereas incongruent patterns are those where arrows for each dimension end at different points.

In Experiment 1A, two types of induction sequences, increasing (n = 13) or decreasing (n = 12) frequency, served as a between subjects variable. Within subjects variables included frequency range (low, mid, and high) and frequency shift of the probe tone (-70 c, -35 c, 0 c, +35 c, and +70 c). This resulted in a 2 x (3 x 5) mixed factorial design and a total of 30 unique sequences. In each group, listeners heard the 15 patterns associated with a particular frequency pattern (increasing or decreasing) six times.

In Experiment 1B, two types of induction sequences, increasing (n = 17) or decreasing (n = 18) frequency, served as a between subjects variable. Within subjects variables included intensity pattern of the induction sequence (constant loud, increasing, decreasing, and constant soft), frequency range (low, mid, and high), and frequency shift of the probe tone (-70 c, -35 c, 0 c, +35 c, and +70 c). This resulted in a 2 x (4 x 3 x 5)
mixed factorial design and a total of 120 unique sequences. In each group, listeners heard the 60 patterns associated with a particular frequency pattern (increasing or decreasing) three times.

**Procedure.** All participants heard recorded instructions and saw a schematic of the task. They were instructed to press a button on a Midilab response panel indicating whether the probe tone was the same pitch as the final tone of the induction sequence or different, and to make this response as quickly and accurately as possible. In addition, participants in Experiment 1B were instructed to ignore any change in loudness, because it is irrelevant to the task.

Participants in Experiment 1A received 6 practice trials (with corrective feedback), followed by 3 test blocks of 60 trials each (no feedback). Participants in Experiment 1B received 12 practice trials (with corrective feedback), followed by 4 test blocks of 45 trials each (no feedback). Presentation of sequences was randomized, with the constraint that each block contained an equal number of sequences for each level of the within subjects variables. At the conclusion of the experiment, participants filled out a questionnaire regarding their musical experience and their impressions of the task.

**Dependent Measures.** Both error shifts and accuracy scores were evaluated in this, and subsequent, experiments. Error shifts, or weighted measures (WMs), reflect a listener’s bias toward responding ‘same’ to higher or lower probes. As discussed in Chapter 1, the WM is calculated by averaging the proportion of ‘same’ responses weighted by the frequency shift of the probe. The result is a single number whose sign indicates the direction of error shift, and value is in an index of the magnitude of the error shift (larger values indicate greater shift in errors).
In addition, accuracy was also calculated using proportion correct (PC). Small WMs, close to zero, can indicate very accurate performance or simply that errors are evenly distributed between higher and lower probes. Analysis of PC data allows this distinction to be made.

**Results**

Table 3.5 presents average WM and PC scores for all conditions in Experiment 1 as a function of frequency direction and intensity pattern, collapsed over the frequency range variable. Figure 3.4 presents average WM scores for each frequency direction as a function of intensity pattern, and “C” denotes congruent induction sequences and “I” denotes incongruent induction sequences.

**WM analyses**

**Experiment 1A.** A mixed ANOVA was conducted using WMs, with frequency pattern as a between subjects variable and frequency range as a within subjects variable. This revealed only a main effect of frequency direction, $F(1, 23) = 23.98$, $MSE = 233.34$, $p < .001$. WM scores differed significantly for increasing frequency (WM = +8.40) versus decreasing frequency (WM = -8.88). This replicates findings in the auditory RM literature (Freyd, et al., 1990; Hubbard, 1995a; Kelly & Freyd, 1987), in that errors are shifted in the direction implied by the sequence.

**Experiment 1B.** First a repeated measures ANOVA was conducted on the WMs from the group receiving increasing frequency patterns, with intensity pattern and
frequency range serving as within subjects variables. This revealed a main effect of intensity pattern, $F (3, 48) = 8.18, MSe = 75.49, p < .001$. WMs for intensity patterns that were increasing in loudness (WM = +2.91) or constantly loud (WM = +3.84) were shifted in the direction implied by the frequency pattern of the induction sequence and WMs with these sequences were significantly different from those found with constant soft intensity patterns (WM = -3.75) which were shifted in the opposite direction (Tukey HSD, $p < .05$). With increasing frequency patterns, errors were shifted in the direction implied by the preceding pitch trajectory, i.e., positive WMs, for congruent patterns (increasing or constant loud intensity); and by contrast, the magnitudes of WMs were much smaller and reversed, as evidenced by negative WMs, for incongruent patterns (decreasing or constant soft intensity).

In addition, with these increasing frequency patterns, there was a main effect of frequency range, $F (2, 32) = 5.24, MSe = 243.93, p = .01$. In general, listeners were more likely to respond ‘same’ to higher probes with low frequency range patterns (WM = +5.21) and more likely to respond ‘same’ to lower probes with mid frequency range patterns (WM = -3.39), (Tukey HSD, $p < .05$). Pitch judgments with high frequency range patterns (WM = -0.58) fell between, with WMs close to zero. Although the frequency range variable had an effect on pitch judgments, this did not interact with intensity pattern.

For the group of listeners receiving decreasing frequency patterns, a similar repeated measures ANOVA using WMs revealed a main effect of intensity pattern, $F (3, 51) = 9.95, MSe = 93.25, p < .001$. All WMs were shifted in the direction implied by the frequency pattern of the induction sequence, i.e., negative WMs. However, the magnitude
of WMs for the increasing intensity (WM = -1.90) and constantly loud (WM = -1.09) patterns were significantly smaller than the WMs for the decreasing intensity (WM = -9.75) and constant soft (WM = -7.03) patterns, (Tukey HSD, $p < .05$). Thus, for decreasing frequency patterns, errors were shifted in the direction of the preceding pitch trajectory and for congruent patterns (decreasing or constant soft intensity) the magnitudes of WMs were much greater than the magnitudes of WMs for incongruent patterns (increasing or constant loud intensity).

In addition, with decreasing frequency patterns, there was a main effect of frequency range, $F(2, 34) = 6.66, MSe = 166.31, p < .01$. Again, WMs were shifted in the direction implied by the frequency pattern of the induction sequence, however greater extrapolation occurred for mid (WM = -9.46) frequency range patterns than for low (WM = -2.38) and high (WM = -2.99) (Tukey HSD, $p < .05$). This main effect was qualified by a significant interaction of intensity pattern with frequency range, $F(6, 102) = 5.84, MSe = 61.16, p < .001$. Tukey HSD post hoc tests indicated that this interaction essentially mirrored the main effect of intensity; that is, for low frequency range patterns the magnitude of WMs for increasing, loud, and soft intensity patterns were significantly smaller than WMs for decreasing patterns, for mid patterns the WMs for increasing intensity patterns were significantly smaller than WMs for decreasing patterns, and no significant differences occurred with high patterns. Although the frequency range variable had an effect on pitch judgments, this did not appear to impact the types of errors associated with each intensity pattern.

**Experiment 1A vs. 1B.** Planned comparisons were conducted to investigate whether varying intensity influenced error shifts differently as compared to the errors
observed in Experiment 1A, where intensity was not varied. The analyses detailed below indicate that congruency between frequency and intensity within the induction sequence did affect error shifts. Although error shifts with congruent sequences in Experiment 1B were similar to error shifts in Experiment 1A, this was not so with the incongruent sequences in Experiment 1B.

First, WMs from the increasing frequency pattern groups of Experiment 1A and 1B were compared. WMs did not differ between Experiment 1A and congruent patterns in Experiment 1B, i.e., increasing intensity and constant loud. However, performance in Experiment 1A differed significantly from performance with incongruent patterns in 1B i.e., decreasing intensity and constant soft. Specifically, in Experiment 1A listeners were more likely to respond ‘same’ to higher probes (WM = +8.40) and in Experiment 1B listeners were more likely to respond ‘same’ to lower probes with both decreasing intensity (WM = -0.64) \([F (1, 28) = 7.24, MSe = 249.7, p = .01]\) and the constant soft patterns (WM = -3.75) \([F (1, 28) = 10.35, MSe = 315.49, p = .003]\). Thus, observed error shifts for congruent patterns were equivalent to observed error shifts with the increasing frequency patterns of Experiment 1A; errors reflected extrapolation of the increasing frequency trajectory. In contrast, with incongruent versions of these patterns, the error shift was greatly reduced as compared to the error shifts in Experiment 1A.

Next, WMs from the decreasing frequency pattern groups of Experiment 1A and 1B were compared. A similar outcome was observed for these patterns. Again the WMs did not differ between Experiment 1A and congruent patterns in Experiment 1B, i.e., decreasing intensity and constant soft. In addition, performance in Experiment 1A differed significantly from performance with incongruent patterns in 1B, i.e., increasing
intensity and constant loud. Specifically, in Experiment 1A error shifts were large ($WM = -8.88$) and in Experiment 1B the error shifts were much smaller with both increasing intensity ($WM = -1.90$) [$F(1, 28) = 5.64, MSe = 186.62, p = .02$] and the constant loud patterns ($WM = -1.09$) [$F(1, 28) = 4.75, MSe = 275.84, p = .04$]. Thus, observed error shifts for congruent patterns were equivalent to observed error shifts with the decreasing frequency patterns of Experiment 1A; errors reflected extrapolation of the decreasing frequency trajectory. In contrast, with incongruent versions of these patterns, the error shift was greatly reduced as compared to the error shifts in Experiment 1A.

In sum, for both increasing and decreasing frequency patterns, congruent versus incongruent intensity patterns had an impact on performance across the two experiments. Errors were shifted in the direction implied by the preceding pitch trajectory when intensity was held constant throughout the experiment (1A) and when intensity and frequency were congruent, i.e., positively correlated, in Experiment 1B. These results are consistent with predictions from both the pattern-based expectancy hypothesis and the dimensional interaction hypothesis. However, with the incongruent patterns of Experiment 1B, where intensity and frequency were negatively correlated, the magnitude of error shifts significantly decreased and with increasing frequency patterns the direction of errors actually reversed. Taken together, these findings suggest that congruency does not necessarily facilitate extrapolation but incongruency appears to reduce this shift in errors. This result is consistent only with predictions from the dimensional interaction hypothesis.

*PC analyses*
**Experiment 1A.** A mixed ANOVA was performed on PC data, with frequency pattern as a between subjects variable and frequency range as a within subjects variable. This analysis revealed no significant main effects or interactions. Average PC was .74 and .73 for the increasing and decreasing frequency groups, respectively.

**Experiment 1B.** For the group receiving increasing frequency patterns, a repeated measures ANOVA was conducted on the PC scores, with intensity pattern and frequency range serving as within subjects variables. This analysis revealed no significant main effects or interactions. Accuracy was essentially equivalent with all intensity patterns. These results, combined with the WM results, indicate that although errors were systematically shifted toward higher probes with congruent patterns and lower probes with incongruent patterns, accuracy was similar for all intensity patterns. In addition, examining standard errors revealed that variability, on average, was similar for both congruent and incongruent patterns.

A similar repeated measures ANOVA was conducted on the PC scores for listeners who received decreasing frequency patterns. This analysis revealed a significant main effect of intensity pattern, $F (3, 51) = 8.64, MSE = 0.01, p < .0001$. Tukey HSD post hoc tests indicated that performance was generally worse with increasing intensity (PC = .68) versus both constant soft (PC = .79) and decreasing intensity (PC = .76) patterns; and performance was worse with constant loud (PC = .71) versus constant soft intensity patterns. Essentially, accuracy was worse for incongruent patterns (decreasing frequency with increasing intensity and decreasing frequency with constant loud intensity) compared to congruent patterns.
These results are consistent with predictions of the dimensional interaction hypothesis and the isolated tone pairs hypothesis. These hypotheses render specific predictions regarding the role of intensity on accuracy. The dimensional interaction hypothesis predicts that performance is better with congruent sequences than with incongruent sequences. The isolated tone pairs hypothesis predicts that performance is better with low intensity probe tones than with high intensity probe tones. Unfortunately, congruency and final intensity level are confounded in this experiment. For decreasing frequency patterns, congruent sequences are necessarily lower in intensity and incongruent sequences are necessarily higher in intensity. Because similar effects were not found with the increasing frequency patterns, it is not possible to determine if this difference in accuracy is due to congruency or final intensity level. Subsequent experiments should help make this determination.

Considering the observed WMs, these PC results indicate that even though the magnitudes of error shifts were small for incongruent patterns, listeners were not more accurate with incongruent patterns versus congruent patterns. For decreasing frequency patterns, more pitch judgment errors occurred with incongruent versus congruent patterns. However, these errors were evenly distributed between higher and lower pitch probes instead of being shifted predominantly toward lower probes. Finally, despite differences in PC and WMs, variability, on average, was similar for both congruent and incongruent patterns.

*Discussion*
The results of Experiment 1A, which contained no intensity manipulations, replicate the basic findings in the auditory RM literature (Freyd, et al., 1990; Hubbard, 1995a; Kelly & Freyd, 1987), in that listeners' pitch judgment errors were shifted in a direction consistent with continuation of the frequency trajectory implied by the induction sequence. More importantly, the results from Experiment 1B indicate that intensity changes within the induction sequence also influence pitch judgment errors.

Analyses of Experiment 1B revealed that errors were differentially affected by congruency between the frequency and intensity patterns in the induction sequence. This is evidenced by three main findings. First, with congruent patterns, pitch judgment errors were shifted in the direction implied by the preceding frequency trajectory. These errors reflected continuation of the experienced frequency pattern; moreover the direction and magnitude of these errors were similar to the errors from Experiment 1A, which contained no intensity changes. Second, with incongruent patterns, pitch judgment error magnitudes were generally small, i.e., WMs close to zero. In addition, although the WMs were small their direction was actually reversed for the incongruent patterns with increasing frequency. The latter implies that incongruent patterns did not elicit continuation of the experienced frequency pattern; moreover, the direction and magnitude of these errors were not comparable to the error shifts in Experiment 1A, which contained no intensity changes. Third, despite the differential affects of congruency on the direction and magnitude of error shifts, the mean and variability of accuracy scores (PC) were generally similar for intensity patterns. Therefore, the lower WM scores observed with incongruent patterns do not reflect greater overall accuracy with these sequences. Rather, lower WM scores indicate that errors were more evenly distributed between higher and
lower pitch probes instead of being shifted predominantly toward probes whose pitch preserves the experienced frequency trajectory. In fact, the only effect of intensity on accuracy was obtained with decreasing frequency patterns and in this case accuracy was greater with congruent patterns versus incongruent patterns.

**Evaluation of Four Hypotheses**

These results shed light on predictions from four hypotheses as presented in Figure 3.3. First, the *environmental invariants hypothesis* suggests that intensity could be analogous to mass. Therefore, the magnitude of error shifts should be greater for both increasing and constant loud intensity conditions as compared to decreasing and constant soft intensity conditions. These results were not obtained. In fact, with decreasing frequency sequences the exact opposite pattern of results predicted by this hypothesis were observed.

Second, the *pattern-based expectancy hypothesis* predicts that the direction of error shifts will be consistent with continuation of the experienced frequency pattern. This prediction is obtained for congruent increasing frequency sequences and with both congruent and incongruent decreasing frequency sequences. This provides some support for this hypothesis. However, this hypothesis does not offer specific predictions regarding how intensity patterns within the induction sequence will influence pitch judgments; consequently, it cannot explain why error magnitudes were reduced for incongruent sequences versus congruent sequences.

Third, the *isolated tone pairs hypothesis* posits that increasing intensity yields decreased perceived pitch. This hypothesis predicts that pitch judgments should be very accurate (higher PC) with decreasing intensity and constant soft probes and less accurate
with increasing intensity or constant loud probes. Limited support for the accuracy prediction was obtained with the decreasing frequency sequences of Experiment 1B, where PC was higher with low intensity probes versus high intensity probes. However, final intensity level and congruency are necessarily confounded with these patterns, meaning that for congruent sequences probes are always low pitch and soft and for incongruent sequences probes are always low pitch and loud. More importantly, this hypothesis also predicts that with louder tones perceived pitch is lower, thus errors should be shifted toward low frequency probes with increasing intensity and constant loud sequences. These results do not obtain. Although there is some support for the isolated tones pairs’ predictions regarding PC, the majority of the experimental results suggest that this hypothesis does not generalize well to the pitch judgments in this task, which employs longer auditory sequences.

Finally, the dimensional interaction hypothesis is the only hypothesis which assumes that the monotonic configurations of pitch and loudness may interact, leading to congruency effects. Considering the adaptation of dimensional interaction research to the tone sequences used here, it can be predicted that errors (WMs) will be shifted in a direction consistent with continuation of the linear frequency trajectory. In this case, one interpretation of the dimensional interaction hypothesis implies that the absolute magnitude of error shifts should be greater when pitch and loudness changes are positively correlated (congruent) than when they are negatively correlated (incongruent). The observed WM results are most consistent with this hypothesis. As predicted, error shifts reflected differential effects of congruency. Specifically, with congruent sequences errors were shifted in a direction consistent with continuation of the monotonic frequency
trajectory. With incongruent sequences error shifts were greatly reduced, or for increasing frequency sequences the direction of the error shift actually reversed. In addition, this hypothesis predicts that listeners will be more accurate (higher PC) at judging congruent versus incongruent probe tones. Evidence of this was found with the decreasing frequency sequences of Experiment 1B; pitch judgments were more accurate (higher PC) for congruent versus incongruent patterns. However, congruence was confounded with final intensity level. Thus, it is unknown whether decreased accuracy was due to higher final intensity level or incongruent frequency and intensity values.

One final aspect of the data which should be discussed concerns the confounding, in Experiment 1B, between intensity pattern and final intensity level. Regardless of the frequency pattern, increasing and constant loud intensity patterns always have a final intensity of 79 dB and decreasing and constant soft intensity patterns always have a final intensity of 65.5 dB. Possibly errors could reflect a bias towards higher probes with louder final intensities and a bias towards lower probes with softer final intensities. The results of Experiment 1B show some consistency with this explanation, especially with increasing frequency patterns. However, results from a previous pilot study rule out this interpretation. In this pitch judgment study, stimuli consisted of two tones on each trial that were equivalent to the final induction sequence tones and the probe tones used in Experiment 1B. Results showed that intensity level had no influence on error shifts or accuracy.

In summary, the results of Experiment 1B rule out two of the four hypotheses outlined in Chapter 2 and in the introduction to Experiment 1. Both the environmental invariants and isolated tone pairs hypotheses fail to account for major aspects of
Experiment 1 results. Instead support is found for both the pattern-based expectancy hypothesis and the dimensional interaction hypothesis. The former hypothesis predicts that error shifts will reflect only a continuation of the experienced frequency pattern, regardless of intensity variations. The latter hypothesis correctly predicts that congruent versus incongruent patterns will yield different error shifts (WMs). Plus it predicts overall higher accuracy when frequency and intensity are congruent versus incongruent.

A New Hypothesis

Support for the pattern-based expectancy hypothesis and the dimensional interaction hypothesis is obtained in Experiment 1, however both of these hypotheses have limitations. The former cannot explain how intensity variations influence pitch judgments whereas the later does not extend to non-monotonic patterns. I propose a combination of these two hypotheses as a new, alternative, hypothesis. This is the pattern congruency hypothesis. This hypothesis was developed to address both complex pattern structure and dimensional congruency. Essentially, it applies the notion of congruency to describe patterns as a whole. This new hypothesis assumes that a congruent pattern is formed when the frequency and intensity of tones within a sequence change over time in a similar manner. These changes may create simple linear patterns or more complex patterns, such as the periodic patterns used in the following experiments. Therefore, pattern structure is associated with the relationships between nonadjacent as well as adjacent tones within a sequence and is not limited to correlations over adjacent serial locations with the lower-order pattern structure, as dictated by the dimensional interaction hypothesis. A second feature of the pattern congruency hypothesis concerns task-relevance. In all of the experiments in this study, intensity variations are irrelevant to the
task. However, this hypothesis assumes that when an intensity pattern is congruent with a frequency pattern, it is very difficult for listeners to ignore intensity variations. In this case, the frequency pattern, which is the relevant dimension, is reinforced and errors are shifted in the direction implied by the overall frequency pattern. Conversely, when an intensity pattern is incongruent with a frequency pattern, the irrelevant intensity pattern may be distracting. In this case, the frequency pattern may not be as compelling and systematic shifts in pitch judgment errors will be greatly reduced. As an ad hoc hypothesis, the pattern congruency hypothesis provides a better explanation of the observed error shifts in Experiment 1B than either the pattern-based expectancy hypothesis or the dimensional interaction hypothesis.

Summary

The main goal of Experiment 1 was to investigate how intensity changes within a monotonic frequency pattern influence pitch judgments of a subsequent probe tone. Following a preliminary rating study, intensity values that paralleled changes in frequency values were selected to construct intensity variations for the monotonic frequency patterns used in Experiment 1. Experiment 1A presented linear frequency patterns that contained no intensity changes. The results of Experiment 1A replicated the findings in the auditory RM literature; errors (WMs) were shifted in the direction implied by the frequency pattern of the induction sequence. In Experiment 1B congruent and incongruent intensity changes were added to these frequency patterns. Despite the fact that intensity was an irrelevant dimension in this task, congruency influenced pitch judgments. Specifically, errors were shifted in the direction implied by the frequency
pattern with congruent patterns and error magnitudes were greatly reduced with
incongruent patterns. In addition, with decreasing frequency patterns in Experiment 1B,
PC was higher for congruent versus incongruent sequences.

Four hypotheses were evaluated. The results of Experiment 1B rule out the
environmental invariants and isolated tone pairs hypotheses. Support was found for both
the pattern-based expectancy and the dimensional interaction hypotheses. Finally, a
pattern congruency hypothesis was proposed. This hypothesis combines successful
aspects of both the pattern-based expectancy and dimensional interaction hypotheses, and
provides the best account of these data.
<table>
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<tr>
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<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Increasing Frequency</td>
<td>D₅</td>
<td>E₅ + 25 c</td>
<td>Gf₅ + 50 c</td>
<td>Af₅ + 75 c</td>
</tr>
<tr>
<td>Low sequence</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mid sequence</td>
<td>E₅ + 25 c</td>
<td>Gf₅ + 50 c</td>
<td>Af₅ + 75 c</td>
<td>B₅</td>
</tr>
<tr>
<td>High sequence</td>
<td>Gf₅ + 50 c</td>
<td>Af₅ + 75 c</td>
<td>B₅</td>
<td>Df₆ + 25 c</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Tone</th>
<th>1</th>
<th>2</th>
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<tbody>
<tr>
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<td>Low sequence</td>
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</tr>
<tr>
<td>Mid sequence</td>
<td>B₅</td>
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<td>Gf₅ + 50 c</td>
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<tr>
<td>High sequence</td>
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<td>B₅</td>
<td>Af₅ + 75 c</td>
<td>Gf₅ + 50 c</td>
</tr>
</tbody>
</table>

Table 3.1. Frequency values in musical notation for each standard sequence tone as a function of increasing or decreasing frequency and frequency range, in the rating experiment.
Table 3.2. Intensity values in dB for each comparison sequence tone as a function of increasing or decreasing intensity and intensity change, in the rating experiment.
<table>
<thead>
<tr>
<th>Frequency Direction</th>
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<th>4.5</th>
<th>6</th>
</tr>
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<tbody>
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<td>.551</td>
<td>.560</td>
<td>.537</td>
</tr>
<tr>
<td>Decreasing</td>
<td>.310</td>
<td>.486</td>
<td>.647</td>
<td>.523</td>
</tr>
<tr>
<td>Average</td>
<td>.351</td>
<td>.523</td>
<td>.597</td>
<td>.531</td>
</tr>
</tbody>
</table>

Table 3.3. Proportion of “similar amount of change” responses (ratings of 5, 6, and 7), in the rating experiment.
Table 3.4. The frequency and intensity induction sequence patterns in Experiment 1. Solid arrows denote frequency and dashed arrows denote intensity.
Table 3.5. WMs for each frequency pattern, as a function of intensity pattern, in Experiment 1. PC scores are inside parentheses.
Figure 3.1. Example of a standard-comparison sequence from the rating experiment. The standard increases in frequency and the comparison increases in loudness (darker circles represent louder tones). The frequency of the tones in this comparison sequence are identical to the frequency of the 3rd tone in the standard sequence.
Figure 3.2. Example of three different types of induction sequences from Experiment 1B (darker circles represent louder tones). Four tone induction sequences are followed by a probe tone (hatched circle) that can vary in frequency.
Figure 3.3. Experiment 1B error shift (WM) predictions from four hypotheses. WMs are shown for four intensity conditions as a function of two frequency pattern conditions. In Panel D, “C” indicates congruent sequences and “I” indicates incongruent sequences.
Figure 3.4. WMs for all conditions in Experiment 1; “C” denotes congruent sequences
and “I” denotes incongruent sequences.
CHAPTER 4
PERIODIC, HIGHER-ORDER INTENSITY AND FREQUENCY PATTERNS

The sounds that listeners typically encounter in their auditory environment change dynamically in pitch and loudness. For instance, auditory patterns in both speech and music may rise and fall in pitch and/or intensity over an extended period of time. In Experiment 2 longer patterns are used that involve a more complex pattern than in Experiment 1. Thus, the number of tones that comprise an induction sequence is increased (relative to Experiment 1) in order to create auditory sequences that imply periodic increasing and decreasing motion in frequency space. These patterns are similar to those used by Johnston and Jones (in press), as described in Chapter 1. However in the present experiment we continue to consider the effects of intensity patterns on pitch judgments. Thus tones also increase and decrease in intensity throughout the course of these longer sequences. These manipulations create sequences with frequency and intensity structure that transpires over two related time levels, a lower-order and a higher-order time level. The lower-order level in these sequences refers to the time spans that are associated with linear (monotonic) changes in frequency and intensity between adjacent tones. The higher-order level, by contrast, refers to time spans that are associated with the (non-adjacent) period boundaries, i.e., peaks and troughs, of the periodic frequency and intensity pattern. As in Experiment 1B, the frequency and intensity patterns are again crossed in this design (see Table 4.1). However, in this experiment they create congruent
and incongruent sequences that are periodic in nature. Examples of congruent and incongruent periodic sequences, used in Experiment 2, appear in Figure 4.1, Panels A and B respectively.

Recall that using similar frequency patterns, Johnston and Jones (in press; Figure 1.1) found that when a to-be-judged probe tone occurred at a period boundary, listeners’ errors (WMs) reflected a sensitivity to the forthcoming change within the higher-order periodic pattern, not to the direction of the immediately preceding, i.e., lower-order, frequency trajectory. In other words, listeners’ judgments were consistent with a systematic anticipation of future sequence elements based on higher-order structure. In a comparable visual RM study, Verfaillie and d’Ydewalle (1991) concluded that evidence of attending to the higher-order pattern is obtained when WMs at a period boundary are reversed or close to zero. It is important to note that they include WMs that are close to zero as evidence of higher-order attending because small WM values are very different from the observed WMs obtained with monotonic induction sequences. Typically when listeners rely only on lower-order structure, as with the monotonic sequences in Experiment 1, error shifts (WMs) are large and in the direction consistent with continuation of the immediately preceding trajectory. However, Johnston and Jones (in press) found that with periodic frequency patterns, error shifts were large and reversed at period boundaries. In the present research the criterion used to determine that listeners are attending to the higher-order pattern structure is a WM either near zero or reversed.

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3 A reversed WM is a WM whose sign indicates that errors are shifted in the direction inconsistent with continuation of the immediately preceding monotonic frequency trajectory. For example, a positive WM for a probe that follows a sequence of tones that decrease in frequency is a reversed WM.
The goal of Experiment 2 is to build upon the findings of Johnston and Jones (in press) by examining the influence of periodic intensity patterns upon extrapolations of a pitch pattern. Of particular interest is the possible role that frequency/intensity congruence may play in highlighting for listeners the higher-order (periodic) structure versus the lower-order (linear) structure in these sequences. Findings from this experiment should shed some light on this issue and provide related support for one of the hypotheses discussed below.

Three hypotheses are relevant to Experiment 2. All were outlined in Chapter 3; they are the pattern-based expectancy hypothesis, the dimensional interaction hypothesis, and the pattern congruency hypothesis. These hypotheses were chosen because they successfully described data that were observed in Experiment 1B. Similar to Experiment 1, the primary measure used to evaluate these hypotheses is a weighted measure (WM), which indexes biases in errors; although supplemental analyses of overall accuracy, using proportion correct (PC), are also informative.

Comparative evaluations of the three hypotheses of interest are more telling at certain points within these periodic patterns than at other points. Considering the structure of the periodic patterns used in this experiment, length 10 is a period boundary, i.e., the location of a higher-order direction change, and offers the clearest test of these hypotheses. WM values at length 10 will be indicative of 1) whether listeners are focused on the lower-order (linear) or higher-order (periodic) frequency pattern, and 2) whether or not error shifts are modulated by congruency between frequency and intensity. Specifically, the sign of the observed WM will indicate whether listeners are focused on the lower-order or higher-order frequency pattern. For example, given a length 10 FA
pattern, serial position 10 is a frequency trough, with preceding tones falling in pitch and subsequent tones rising in pitch. If WMs for length 10 sequences are negative, this indicates that errors reflect continuation of the lower-order frequency trajectory. If WMs for length 10 sequences are positive, this indicates that listeners are anticipating the pitch reversal associated with the higher-order pattern. In addition, the absolute magnitude of WMs will indicate whether error shifts are modulated by congruency. For example, larger WMs may be observed for congruent sequences compared to smaller WMs for incongruent sequences.

Predictions regarding experimental outcomes at the critical length 10 period boundary are offered by the three hypotheses. These are graphically displayed in Figure 4.2. In Panels A, B, and C of Figure 4.2, the predicted direction and magnitude of error shifts (WMs) are plotted for each hypothesis for the two frequency patterns (F_A and F_B) as a function of intensity pattern congruency (congruent and incongruent) for induction sequences of length 10. Of course, length 13 may also be considered a period boundary if sequences were to continue. However, listeners quickly become aware that that induction sequences will never be longer than 13 tones and this knowledge may influence whether they are focused on either the higher-order or lower-order frequency pattern. Johnston and Jones (in press) have reported evidence that listeners’ error shifts were consistent with the higher-order frequency patterns at length 13; therefore, it will be informative to examine errors at this length. Predictions regarding possible error shifts at length 13 are graphically displayed in Panels A, B, and C of Figure 4.3 for the three hypotheses under

4 Based on the criterion outlined earlier and the findings of Verfaillie and d’Ydewalle (1991), WMs that are close to zero also indicate that listeners are anticipating a pitch reversal consistent with the higher-order frequency pattern.
consideration. Nevertheless, because of the possibility of end anticipation effects, length 10 instead of 13 is deemed to provide the clearest point, i.e., critical location, for detecting any influence of higher-order patterns on pitch judgments. In the following theoretical discussion, the primary comparisons of different hypotheses are considered for the critical length 10 period boundary.

Consider first the pattern-based expectancy hypothesis. Predictions are depicted in Panel A of Figures 4.2 and 4.3. This hypothesis emphasizes continuation of the frequency pattern and hence predicts that the direction of WMs will reflect continuation of the higher-order frequency pattern. In addition, this hypothesis makes no predictions regarding accuracy. Thus with sequences of length 10, WMs for FA patterns should be positive and WMs for FB patterns should be negative (note that the signs of the WMs are reversed for length 13). This is consistent with the findings of Johnston and Jones (in press).

Second, predictions from the dimensional interaction hypothesis appear in Panel B of Figures 4.2 and 4.3. This approach predicts that the direction of error shifts will reflect extrapolation of the linear (lower-order) frequency trajectory and the predicted magnitude of errors will be relatively greater for positively correlated, i.e., congruent, compared to negatively correlated, i.e., incongruent, sequences. Thus, at length 10, WMs for FA patterns should be negative and for FB patterns WMs should be positive, consistent with continuation of the lower-order trajectory (note that the signs of the WMs are reversed for length 13) and error shifts should be greater for the congruent sequences as compared to the incongruent sequences. In short, the most important consequence of these predictions is the assumption that dimensional congruency operates on the lower-
order sequence structure and is associated with correlations over adjacent serial locations. In other words, dimensional congruence, but not pattern congruence, is evident only over monotonic (four tone) segments, i.e., locally, much as evident in Experiment 1. Thus, error shifts that anticipate directional changes at period boundaries would not be predicted. In addition, this approach predicts that pitch judgments should be more accurate (PC) with congruent versus incongruent probe tones.

Finally, predictions from the new pattern congruency hypothesis appear in Panel C of Figures 4.2 and 4.3. This approach applies the notion of congruency to describe patterns as a whole. When the frequency and intensity of tones within a sequence change in a similar manner, whether the changes are linear or periodic, they lead to a congruent pattern. Thus, the structure of such patterns may be simple or complex. This hypothesis also is concerned with task relevance. It assumes that when an intensity pattern is congruent with a frequency pattern, it should be difficult for listeners to ignore intensity variations even though they are irrelevant in this experiment, i.e., these sequences should form a powerfully integrated pattern. As a result, the relevant frequency dimension is reinforced and errors are shifted in the direction implied by the overall frequency pattern. This bias should be reduced when irrelevant intensity variations form an incongruent pattern. Therefore, this hypothesis predicts that error shifts will be large and in the direction consistent with continuation of the higher-order frequency pattern with congruent patterns and that error shifts in this direction will be smaller when the frequency and intensity changes form an incongruent pattern. Relating this to the critical length 10 period boundary, WMs for \( F_A \) patterns should be positive and WMs for \( F_B \) patterns should be negative, reflecting the higher-order frequency pattern (note that the
signs of the WMs are reversed for length 13). Plus, the absolute magnitude of the error shifts should be greater for the congruent sequences as compared to the incongruent sequences. Finally, as with the pattern-based expectancy hypothesis, the pattern congruency hypothesis makes no predictions about accuracy.

Experiment 2 is divided into two parts (as in Experiment 1). In Experiment 2A induction sequences are periodic increasing and decreasing frequency patterns that contain no intensity variations. The goal of this experiment is to replicate the findings of Johnston and Jones (in press). In Experiment 2B induction sequences are the same periodic increasing and decreasing frequency patterns however intensity is also manipulated. Each sequence contains increasing and decreasing intensity changes and these patterns are crossed with the pattern of frequency changes to create congruent and incongruent sequences.

Method

Subjects. Ninety-eight undergraduate students with normal hearing and fewer than ten years of formal musical training (mean = 1.4 years) participated in this experiment in exchange for credit in the introductory psychology course at The Ohio State University. The data from three participants were discarded, one participant responded to fewer than 80% of trials, one participant’s overall accuracy was less than 30%, and one participant responded “different” on every trial.

Apparatus. All equipment used was identical to the rating experiment.

Stimuli. All patterns were composed of induction sequences of 10 to 13 tones followed by the to-be-judged probe tone, see Figure 4.1. There were two types of
frequency patterns, $F_A$ and $F_B$. For pattern $F_A$, following the first tone, tones 2, 3, and 4 monotonically decrease in frequency, and then tones 5, 6, and 7 monotonically increase; this undulation is repeated so that tones 8, 9, and 10 monotonically decrease, and finally tones 11, 12, and 13 (when present) monotonically increase. For pattern $F_B$ this pattern is reversed. The length of the sequence determines the frequency of the final tone in an induction sequence. Adjacent tones in the induction sequences were separated in frequency by 225 c, and their values correspond to the low and high frequency ranges used in Experiment 1 (see Table 3.1). The mid frequency range set was excluded in order to keep the total duration of the experiment at one hour. Tones had durations of 250 ms and IOIs of 500 ms. All sequences exhibited frequency structure that transpired over two different (related) time levels. At a lower level, the constant IOI of 500 ms and ISI of 250 ms related successive tones within monotonic four tone sequences (as in Experiment 1); at the higher level, constant period boundaries of 1500 ms marked successive increasing or decreasing frequency trajectories within sequences.

In Experiment 2A, intensity was constant at an intermediate level of 70 dB for all patterns. In Experiment 2B, there were two types of intensity patterns, $I_A$ and $I_B$, see Figure 4.1. For pattern $I_A$, following the first tone, tones 2, 3, and 4 monotonically decrease in intensity, tones 5, 6, and 7 monotonically increase; this undulating pattern is repeated so that tones 8, 9, and 10 monotonically decrease, and finally tones 11, 12, and 13 (when present) monotonically increase. For pattern $I_B$ this pattern is reversed. Adjacent tones in the induction sequences were separated in intensity by 4.5 dB; and their values correspond to the dB values used for increasing and decreasing intensity sequences in Experiment 1, with tones 10 and 13 set at 65.5 dB and 79 dB respectively.
for IA patterns and the reverse for IB patterns. The length of the sequence determines the intensity of the final tone in an induction sequence.

Following each induction sequence in Experiments 2A and 2B, was the to-be judged probe tone. The probe was 250 ms in duration, had the same intensity as the final tone in the induction sequence, and equally often its frequency was the same as the final tone in the induction sequence, lower by 70 c, lower by 35 c, higher by 35 c, or higher by 70 c.

*Design.* The design of Experiment 2 is diagrammed in Table 4.1, where the solid arrows symbolize frequency direction and the dashed arrows symbolize intensity direction. Note that congruent patterns are those with parallel increasing and decreasing arrows whereas incongruent patterns are those with arrows that increase along one dimension and decrease along the other dimension.

In Experiment 2A, frequency pattern, FA or FB, served as a between subjects variable (n = 20 and 18, respectively). Within subjects variables included length of the induction sequence (10, 11, 12, and 13 tones), frequency range (low and high), and frequency shift of the probe tone (-70 c, -35 c, 0 c, +35 c, and +70 c). This resulted in a 2 x (4 x 2 x 5) mixed factorial design, and a total of 80 unique sequences. In each group, listeners heard the 40 patterns associated with a particular frequency pattern (F_A or F_B) three times.

In Experiment 2B, frequency pattern, FA or FB, again served as a between subjects variable, (n = 30 and 27, respectively). Within subjects variables included intensity
pattern of the induction sequence (I_A and I_B)\(^5\), length of the induction sequence (10, 11, 12, and 13 tones), frequency range (low and high), and frequency shift of the probe tone (-70 c, -35 c, 0 c, +35 c, and +70 c). This resulted in a 2 x (2 x 4 x 2 x 5) mixed factorial design, and a total of 160 unique sequences. In each group, listeners heard half of the 80 patterns associated with a particular frequency pattern (F_A or F_B) three times and the other half of the 80 patterns two times.

**Procedure.** All participants heard recorded instructions and saw a schematic of the task. They were told that on each trial they will hear a sequence of 10 to 13 tones followed by a probe tone and that they should just focus on the pitch of the last two tones that they hear. They were instructed to press a button on a Midilab response panel indicating whether the probe tone was the same pitch as the final tone of the induction sequence or different, and to make this response as quickly and accurately as possible. In addition, participants in Experiment 2B were instructed to ignore any changes in loudness, because it is irrelevant to the task.

Participants in Experiment 2A received 12 practice trials (with corrective feedback), followed by 3 test blocks of 40 trials each (no feedback). Participants in Experiment 2B received 12 practice trials (with corrective feedback), followed by 4 test blocks of 50 trials each (no feedback). Presentation of sequences was randomized, with the constraint that each block contained an equal number of sequences for each level of

\(^5\) An additional study was also conducted with intensity pattern as a between subjects variable, instead of as a within subjects variable. The results, detailed in Appendix A, indicate that 1) error shifts are consistent with continuation of the higher-order frequency pattern at period boundaries, and 2) when listeners only receive one type of irrelevant intensity pattern, any effects of pattern congruency are diminished.
the within subjects variables. At the conclusion of the experiment, participants filled out a questionnaire regarding their musical experience and their impressions of the task.

*Dependent Measures.* Same as Experiment 1.

**Results**

Table 4.2 presents the average WM and PC scores for each frequency pattern (F_A and F_B) as a function of intensity pattern (congruent and incongruent) and sequence length, collapsed over the frequency range variable, for all conditions in Experiment 2.

**WM analyses**

**Experiment 2A.** A mixed ANOVA using WMs, with frequency pattern as a between subjects variable and sequence length and frequency range as within subjects variables, revealed only an interaction of frequency pattern with length, \( F(3, 108) = 8.46, MSE = 176.77, p < .001 \). The WMs for this interaction are displayed in Figure 4.4. Trend analyses revealed significant linear trends over sequence length with each frequency pattern \([F_A: F(1, 36) = 7.08, MSE = 234.81, p = .01; F_B: F(1, 36) = 12.11, MSE = 234.81, p = .001]\), along with a significant difference between these trends \([F(1, 36) = 18.97, MSE = 234.81, p < .01]\). These results are consistent with the prediction that the higher-order frequency pattern influences pitch judgments at period boundaries. Specifically, at the critical length 10 period boundary, positive WMs were observed for F_A patterns (+1.36) whereas the remaining WM scores for other lengths were increasingly negative; by contrast, the reverse profile occurs for F_B patterns where negative WMs were observed for length 10 (-5.06) and increasingly positive WM scores for length 12 and 13. Indeed, at length 13 WMs were consistent with the higher-order frequency pattern (F_A WM = -
7.27; $F_B$ WM = +6.33). These results replicate Johnston and Jones (in press), in illustrating that listeners track these patterns as they unfold and that listeners are sensitive to the higher-order structure associated with each experienced frequency pattern.

Further evidence that the higher-order pattern influenced errors comes from comparing the results of Experiment 1A and the length 10 and 13 sequences from Experiment 2A. Note that if only the frequency pattern of the final four tones, i.e., those immediately preceding the probe, are considered, Experiment 2A length 10 $F_A$ sequences are identical to the linearly decreasing patterns of Experiment 1A. Therefore, if the lower-order pattern, corresponding to these monotonic decreases, dominates a listener’s attention, then errors should continue this implied linear motion as in Experiment 1. However, the error shifts at this boundary point are very different, with WMs of +1.36 versus -8.88 for the Experiment 2A length 10 $F_A$ sequences and the decreasing sequences of Experiment 1A respectively. Likewise, the four tones preceding length 10 $F_B$ sequences in Experiment 2A can be compared to the linearly increasing four tone sequences of Experiment 1A; yet the corresponding WMs are -5.06 and +8.40 for Experiments 2A and 1A respectively. Similar differences are found when comparing WMs with Experiment 2A length 13 sequences and Experiment 1A sequences. Errors at period boundaries in Experiment 2A are shifted in the opposite direction of errors with the monotonic frequency patterns of Experiment 1A.

**Experiment 2B.** A mixed ANOVA was conducted using WMs, with frequency pattern as a between subjects variable and congruency, sequence length, and frequency range as within subjects variables. This revealed a main effect of congruency, $F(1, 55) = 7.41$, $MSE = 120.69$, $p < .01$. The overall magnitude of error shifts was greater for
congruent patterns (F_AI_A and F_BI_B) than for incongruent patterns (F_AI_B and F_BI_A), with WMs of +4.96 and +2.98 respectively. In terms of average magnitude, this indicates a greater shift of errors to higher probes with congruent versus incongruent patterns.

There was also a significant interaction of frequency pattern with sequence length, $F(3, 165) = 4.75, MSE = 378.18, p < .01$. The observed WMs for this interaction are presented in Table 4.3. Trend analyses revealed a significant linear trend over sequence length with the F_A pattern [$F_A: F(1, 55) = 5.97, MSE = 579.36, p = .02; F_B: p = .08$], along with a significant difference between the F_A and F_B patterns [$F(1, 55) = 8.78, MSE = 579.36, p < .01$]. These results suggest that the higher-order frequency pattern, not the lower-order linear trajectory, influenced pitch judgments at period boundaries, similar to the findings of Experiment 2A. WMs at length 10 and 13 period boundaries are reversed (length 10 F_A and length 13 F_B) or close to zero (length 10 F_B and length 13 F_A). These results can be interpreted as consistent with the pattern-based expectancy and pattern congruency hypotheses. Both of these hypotheses predict that error shifts at period boundaries should reflect continuation of the higher-order frequency pattern. By contrast, the dimensional interaction hypothesis incorrectly predicts error shifts associated with extension of the lower-order monotonic frequency trajectory; accordingly, it is not supported.

With length 13 F_A patterns, it is unclear whether higher or lower-order structure influenced pitch judgments. The WM indicates a small error shift toward higher probes (WM = +1.51), and because F_A patterns end with a rising frequency trajectory this may be evidence that lower-order structure influenced responding. However, when compared to the linearly increasing sequences of Experiment 1A (WM = +8.40), WMs with the length 13 F_A sequences of Experiment 2B seem greatly reduced, indicating that higher-order structure may have influenced judgments.
The interaction of frequency pattern with sequence length was significant, however this was not qualified by congruency. That is, the three way interaction of frequency pattern, congruency, and sequence length was not significant, \( p = .47 \). Thus, congruency of frequency and intensity did not differentially increase (or decrease) the magnitude of errors at certain locations in the pattern. The relevant WMs are displayed in Figure 4.5 and Table 4.2. Planned comparisons conducted to test for an interaction of frequency pattern and congruency at each sequence length, confirmed that no significant differences were present. And finally, for each frequency pattern, planned comparisons were conducted to investigate whether the magnitude of WMs differed for congruent versus incongruent patterns at each sequence length. One significant difference was found at the critical length 10 period boundary. WMs at this location were larger for the congruent \( F_AI_A \) sequence (WM = +11.87) than WMs for the incongruent \( F_AI_B \) sequence (WM = +5.71), \( F(1, 29) = 4.38, MSE = 260.11, p = .04 \). This finding provides converging evidence to support the pattern congruency hypothesis in that, for \( F_A \) patterns, the direction of error shifts reflects continuation of the higher-order frequency pattern (positive WMs) and the magnitude of the error shift is greater for congruent \( F_AI_A \) versus incongruent \( F_AI_B \) patterns. However, a similar effect was not observed with the \( F_B \) patterns at length 10.

The major point of interest in this experiment concerns differences in WMs based on frequency pattern and congruency at the critical length 10 period boundary. Panel D of Figure 4.2 graphically displays the observed data, along with the predictions from the three hypotheses under consideration (Panels A, B, and C). Error shifts at this location offer the cleanest test of the predictions from the three hypotheses of interest: pattern-
based expectancy, dimensional interaction, and pattern congruency hypotheses. Specifically, WM values can indicate: 1) whether higher-order (periodic) versus lower-order (linear) frequency structure determines performance, and 2) whether or not error shifts are modulated by congruency between frequency and intensity. In examining the observed data, the WMs at length 10 indicate that listeners are focused on the higher-order frequency pattern and that, at least for FA patterns, WMs are modulated by congruency. These results most closely follow predictions from the pattern congruency hypothesis, with observed error shifts at length 10 consistent with all predictions except for congruent FBIB sequences.

Finally, the overall ANOVA also revealed three significant effects related to the frequency range variable. There was a significant interaction of frequency pattern with frequency range \[F (1, 55) = 6.32, MSe = 181.30, p = .01\], a significant interaction of sequence length with frequency range \[F (3, 165) = 13.07, MSe = 297.26, p < .001\], both qualified by a significant interaction of frequency pattern, sequence length and frequency range \[F (3, 165) = 3.19, MSe = 297.26, p = .02\]. The WMs for this three way interaction are displayed in Table 4.4. Tukey HSD post hoc tests \((p < .05)\) revealed that with length 12 FB patterns, listeners were more likely to respond ‘same’ to lower frequency probes with low frequency range sequences (WM = -6.74) and to higher frequency probes with high frequency range sequences (WM = +11.00). Although there were differences associated with frequency range, this variable did not interact with congruency.

Experiment 2A vs. 2B. Analyses were conducted to investigate whether varying intensity in Experiment 2B influenced pitch judgments as compared to Experiment 2A, where intensity was not a variable; see Table 4.2. A similar analysis in Experiment 1,
indicated that WMs for patterns with no intensity variation were comparable to WMs for congruent patterns and very different from WMs for incongruent patterns. In light of this, it is possible that Experiment 2 will show similar affects. If so, such results would suggest that congruency between frequency and intensity within both linear and periodic patterns influences pitch judgments in a similar manner.

Two separate mixed ANOVAs were conducted with WMs. First, the results of Experiment 2A were compared to the results with congruent patterns in Experiment 2B. Second, the results of Experiment 2A were compared to the results with incongruent patterns from Experiment 2B. In the first analysis, experiment (2A versus 2B congruent patterns) and frequency pattern were between subjects variables and sequence length was the within subjects variable. This revealed a main effect of experiment \( F(1, 92) = 11.61, MSE = 259.90, p < .01 \), which was qualified by an interaction of experiment with frequency pattern \( F(1, 92) = 6.18, MSE = 259.90, p = .01 \). Tukey HSD post hoc tests indicated that with \( F_A \) patterns, error shifts differed significantly for the congruent \( F_A I_A \) pattern of Experiment 2B (WM = +6.92) versus the constant intensity \( F_A \) pattern of Experiment 2A (WM = -3.00). Overall, listeners were more likely to respond ‘same’ to high pitched probes with the congruent \( F_A I_A \) pattern in Experiment 2B and more likely to respond ‘same’ to lower pitch probes with the constant intensity \( F_A \) pattern in Experiment 2A. This suggests that for \( F_A \) patterns, congruent intensity variations reinforced the frequency pattern. However, a comparable effect was not observed for the \( F_B \) pattern, with WMs for the congruent \( F_B I_B \) pattern of Experiment 2B (WM = +2.52) statistically equivalent to the WMs for the constant intensity \( F_B \) pattern of Experiment 2A (WM = +0.97).
Perhaps more relevant however, is the absence of significant interactions of experiment with sequence length or of experiment with frequency pattern and sequence length. The WMs for \(F_A\) patterns (Experiment 2A) and for \(F_AI_A\) sequences (Experiment 2B) both yielded similar decreasing linear trends with increasing sequence length; and the WMs for \(F_B\) patterns (Experiment 2A) and for \(F_BI_B\) sequences (Experiment 2B) yielded similar increasing linear trends with increasing sequence length. This finding indicates that the higher-order frequency pattern influences pitch discrimination at period boundaries in a similar manner for both Experiment 2A patterns and Experiment 2B congruent patterns.

In the second analysis, involving Experiment 2A and the incongruent patterns from Experiment 2B, experiment and frequency pattern were between subjects variables and sequence length was the within subjects variable. This revealed a significant interaction of experiment with frequency pattern \([F(1, 92) = 4.72, MSE = 251.51, p = .03]\). Tukey HSD post hoc tests indicated that with \(F_A\) patterns the magnitudes of error shifts were greater for the incongruent \(F_AI_B\) sequences of Experiment 2B (WM = +3.80) versus the constant intensity \(F_A\) pattern of Experiment 2A (WM = -3.00). Again, listeners were more likely to respond ‘same’ to high pitched probes with the incongruent \(F_AI_B\) pattern in Experiment 2B and more likely to respond ‘same’ to lower pitch probes with the constant intensity \(F_A\) pattern in Experiment 2A, similar to the results with the congruent \(F_AI_A\) patterns. There was no difference in WMs between the incongruent \(F_BI_A\) sequences of Experiment 2B (WM = +0.57) versus the constant intensity \(F_B\) pattern of Experiment 2A (WM = +0.97).
In addition there were still no significant interactions of experiment with sequence length or of experiment with frequency pattern and sequence length. The higher-order frequency pattern influenced pitch discrimination at period boundaries in a similar manner for both Experiment 2A patterns and Experiment 2B incongruent patterns. Specifically, the WMs for $F_A$ patterns (Experiment 2A) and for $F_{AI_B}$ sequences (Experiment 2B) both yielded similar decreasing linear trends with increasing sequence length; and the WMs for $F_B$ patterns (Experiment 2A) and for $F_{BI_A}$ sequences (Experiment 2B) yielded similar increasing linear trends with increasing sequence length. With the monotonic sequences used in Experiment 1, incongruent patterns (Experiment 1B) yielded WMs that were decreased compared to WMs with constant intensity patterns (Experiment 1A). However, with the periodic frequency patterns used here, a similar finding was not obtained when WMs for incongruent intensity patterns were compared with WMs for constant intensity patterns.

In summary, for both Experiment 2A and 2B, which employed periodic frequency patterns, error shifts at the critical length 10 period boundary reflected continuation of the higher-order frequency pattern. At this boundary point listeners show a tendency to anticipate a pattern reversal. Although this was observed regardless of whether intensity changes were congruent, incongruent, or absent, an overall effect of congruency was observed in Experiment 2B. The latter outcome took the form of generally larger positive error shifts with congruent than with incongruent sequences, regardless of sequence length. Most importantly, examination of pitch judgment errors at the critical length 10 period boundary revealed error shifts that most closely conformed to predictions of the pattern congruency hypothesis, as shown in Figure 4.2. Supporting this was the finding
that WMs were larger for the congruent $F_A I_A$ sequences than the incongruent $F_A I_B$ sequences. However a similar effect was not obtained with the $F_B I_B$ and $F_B I_A$ sequences, mainly due to the lack of a large reversal for the congruent $F_B I_B$ sequence.

*PC analyses*

**Experiment 2A.** A mixed ANOVA was conducted using PC data, with frequency pattern as a between subjects variable and sequence length and frequency range as within subjects variables. This revealed no differences in accuracy, with an average PC of .65 and .69 for the $F_A$ and $F_B$ groups, respectively. This indicates that despite the large differences in WMs for each frequency group at each sequence length, overall errors were essentially equivalent for all conditions.

**Experiment 2B.** A mixed ANOVA was conducted with frequency pattern as a between subjects variable and congruency, sequence length, and frequency range as within subjects variables. This again revealed no significant main effects or interactions. Accuracy was essentially equivalent across all conditions, with an average PC of .67 and .68 for the $F_A$ and $F_B$ groups, respectively.

In summary, although the direction and magnitude of WMs varied systematically in these experiments, overall performance was neither facilitated nor inhibited by the addition of intensity variations, whether congruent or incongruent, within the induction sequences.

*Discussion*

The results of Experiment 2A, where listeners heard periodic frequency patterns containing no intensity changes, replicate the findings of Johnston and Jones (in press).
The characteristic frequency pattern and sequence length interaction is consistent with extrapolation of the higher-order frequency pattern. That is, error shifts at period boundaries 10 (and 13) were in directions consistent with continuation of the periodic frequency patterns.

Of greater interest are the findings of Experiment 2B where sequences contained intensity variations that were congruent or incongruent with the frequency patterns. In general, performance with the same frequency patterns in both Experiment 2A and 2B was similar in that both yielded significant frequency pattern and sequence length interactions. This is illustrated most clearly by performance at the diagnostic length 10 period boundary. In both experiments, errors at this point were shifted in the direction consistent with continuation of the higher-order frequency patterns.

The results from Experiment 2B show in more detail how intensity changes within the induction sequences influenced errors. This is evidenced by three findings. First, overall the magnitude of error shifts was greater with congruent versus incongruent patterns. This result is similar to the results from Experiment 1B, where the magnitude of error shifts were greater for congruent versus incongruent sequences. Second, at the critical length 10 period boundary, error shifts were significantly larger for the congruent F_A I_A sequences as compared to the incongruent F_A I_B sequences. This frequency pattern (F_A) opens with a falling pitch pattern and ends with a rising one; at location 10, listeners are likely to anticipate this final rising segment by erring in their pitch judgments at this point. The direction of error shifts at this boundary point, in particular, reflects continuation of the higher-order frequency pattern; and the magnitude of this error shift was greater for the congruent versus the incongruent pattern. However, the same outcome
does not hold for the other frequency pattern, F_B, which opens with a rising frequency pattern and ends with a falling frequency pattern. It is noteworthy that error shifts for the F_B\_IB and F_B\_IA sequences at length 10 reflect the higher-order frequency pattern. Yet, at the same time, the magnitude of these error shifts was not modulated by congruency. At location 10, although listeners are likely to anticipate the onset of the final falling segment by erring in their pitch judgments at this point, the magnitude of this error shift was essentially equivalent for congruent and incongruent patterns. Third, when the results from Experiment 2A and 2B were compared, overall WMs were shifted toward higher probes for the F_A\_IA and F_A\_IB sequences of Experiment 2B whereas WMs were shifted toward lower probes with the F_A patterns of Experiment 2A. It is unknown why this general effect obtained with F_A patterns, but a similar difference was not found for F_B patterns.

These results shed some light on predictions from the three hypotheses Experiment 2B was designed to evaluate, as presented in Figures 4.2 and 4.3. Given the structure of these periodic patterns, the length 10 period boundary offers the clearest test of these hypotheses. This is because at length 10, WM values indicate whether listeners are focused on the higher-order (periodic) or lower-order (linear) frequency pattern and whether such error shifts, if they occur, are modulated by congruency between frequency and intensity. Panel D of Figure 4.2 graphically displays the observed WMs for length 10 sequences which can be compared with predictions from the three hypotheses under consideration (Panels A, B and C). In addition, it is also informative to examine WMs for length 13 sequences (Figure 4.3), even though listeners know that induction sequences will never be longer than 13 tones.
First, the *pattern-based expectancy* hypothesis correctly predicts an interaction of frequency pattern with sequence length, with errors shifted in the direction consistent with continuation of the experienced higher-order periodic frequency pattern. Considering the critical length 10 period boundary, WMs for both congruent and incongruent patterns reflect anticipation of the higher-order frequency pattern. [This is also true at length 13 for F_BI_B, F_BI_A, and F_AI_B patterns.] With F_A patterns, where the frequency pattern decreases to tone 10, WMs are positive for both congruent and incongruent patterns, thus reflecting anticipatory errors associated with the upcoming reversal of the frequency pattern. With F_B patterns, where the frequency pattern increases to tone 10, WMs are very close to zero which also suggests that listeners are anticipating a direction change consistent with the higher-order frequency pattern (Verfaillie & d’Ydewalle, 1991). Nevertheless, the pattern-based hypothesis does not explicitly predict how intensity patterns in this experiment should affect pitch judgments. Therefore, although it does correctly predict error shifts consistent with the higher-order pattern, for both frequency patterns, it cannot account specifically for the decrease in the magnitude of WMs for incongruent F_AI_B sequences compared to the larger WMs found with congruent F_AI_A sequences.

Second, the *dimensional interaction hypothesis* predicts that errors should generally differ for congruent versus incongruent patterns, and the main effect of congruency in Experiment 2B supports this prediction. More specifically, this approach predicts that error shifts should reflect a listener’s bias toward simple continuation of implied linear trajectories embedded within these periodic patterns. This pattern of results was not obtained. In addition, this hypothesis predicts greater accuracy (PC) with
congruent versus incongruent sequences, and this result also was not obtained. It seems that the dimensional interaction hypothesis does not generalize well to this task which employs higher-order periodic auditory patterns.

Finally, the pattern congruency hypothesis predicts that when periodic frequency and intensity patterns are congruent, errors will be measurably shifted in the direction consistent with continuation of the higher-order frequency pattern. Conversely, when frequency and intensity patterns are incongruent, the frequency pattern should be less compelling due to the conflicting pattern along an irrelevant dimension. As a result, error shifts will be relatively smaller with incongruent than with congruent patterns. This hypothesis provides a better account of the observed data than either the pattern-based expectancy or the dimensional interaction hypotheses. In agreement with predictions, at the length 10 period boundary $F_A$ patterns yield WMs consistent with continuation of the higher-order frequency pattern and the shift is larger for the congruent pattern compared to the incongruent pattern. In turn, at the length 10 period boundary $F_B$ patterns also yield WMs consistent with continuation of the higher-order frequency pattern. However in conflict with predictions, there is no difference in error shifts for the congruent and incongruent patterns. [WMs with length 13 patterns also conflict with predictions.]

Although this hypothesis can account for some of the findings in this experiment, stronger evidence would have been obtained if an interaction of frequency pattern and congruency at this period boundary had obtained.

Summary
Experiment 2 investigated how pitch judgments of a probe tone are influenced by a preceding induction sequence composed of periodic pitch patterns combined with congruent or incongruent periodic loudness patterns. Experiment 2A, which contained no intensity variations, replicated the findings of Johnston and Jones (in press); in that, errors were shifted in directions consistent with continuation of the higher-order (periodic) frequency patterns. In Experiment 2B, where sequences contained congruent and incongruent intensity patterns, effects of intensity were somewhat limited. Error shifts generally reflected continuation of the higher-order frequency pattern regardless of the intensity pattern. However, there was an overall effect of congruency, with greater overall error shifts with congruent versus incongruent patterns; and, for length 10 $F_A$ patterns, error shifts were greater for congruent compared to incongruent patterns. (A similar effect was not found for $F_B$ patterns.)

The results from Experiment 2B rule out the dimensional interaction hypothesis. The pattern-based expectancy hypothesis correctly predicted that errors would reflect the higher-order frequency pattern, however it cannot account for the congruency effect found with $F_A$ patterns at the length 10 period boundary. The pattern congruency hypothesis was the most successful hypothesis. It correctly predicted that errors would reflect the higher-order frequency pattern and it correctly predicted the congruency effect found with $F_A$ patterns at the period boundary. However, it cannot account for why a similar congruency effect was not found at the length 10 period boundary with $F_B$ patterns.
Table 4.1. The frequency patterns (solid arrows) and intensity patterns (dashed arrows) in Experiment 2 induction sequences.
<table>
<thead>
<tr>
<th>Frequency</th>
<th>Experiment</th>
<th>Intensity</th>
<th>Length</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>10</td>
</tr>
<tr>
<td>F&lt;sub&gt;A&lt;/sub&gt;</td>
<td>Exp 2A</td>
<td>70 dB</td>
<td>+1.36 (.69)</td>
</tr>
<tr>
<td></td>
<td>Exp 2B</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Congruent (I&lt;sub&gt;A&lt;/sub&gt;)</td>
<td>+11.87 (.67)</td>
<td>+7.51 (.63)</td>
</tr>
<tr>
<td></td>
<td>Incongruent (I&lt;sub&gt;B&lt;/sub&gt;)</td>
<td>+5.71 (.61)</td>
<td>+7.73 (.65)</td>
</tr>
<tr>
<td>F&lt;sub&gt;B&lt;/sub&gt;</td>
<td>Exp 2A</td>
<td>70 dB</td>
<td>-5.06 (.69)</td>
</tr>
<tr>
<td></td>
<td>Exp 2B</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Congruent (I&lt;sub&gt;B&lt;/sub&gt;)</td>
<td>+0.22 (.62)</td>
<td>+1.61 (.67)</td>
</tr>
<tr>
<td></td>
<td>Incongruent (I&lt;sub&gt;A&lt;/sub&gt;)</td>
<td>-1.12 (.64)</td>
<td>+1.07 (.64)</td>
</tr>
</tbody>
</table>

Table 4.2. WMs for each frequency pattern, as a function of intensity pattern, in Experiment 2. PC scores are inside parentheses.
<table>
<thead>
<tr>
<th>Frequency</th>
<th>10</th>
<th>11</th>
<th>12</th>
<th>13</th>
</tr>
</thead>
<tbody>
<tr>
<td>$F_A$</td>
<td>+8.79</td>
<td>+7.62</td>
<td>+5.45</td>
<td>+1.51</td>
</tr>
<tr>
<td>$F_B$</td>
<td>-0.45</td>
<td>+1.34</td>
<td>+2.13</td>
<td>+5.38</td>
</tr>
</tbody>
</table>

Table 4.3. WMs for the significant frequency pattern and sequence length interaction in Experiment 2B.
Table 4.4. WMs for the significant interaction of frequency pattern, sequence length, and frequency range in Experiment 2B.
Figure 4.1. Example of a 13 tone induction sequence, followed by a probe tone (hatched circle), from Experiment 2B. Panel A: the congruent $F_{AI_A}$ pattern and Panel B: the incongruent $F_{AI_B}$ pattern. Change in intensity is depicted by shading in the circles, from loud (black) to soft (white).
Figure 4.2. Error shift predictions from three hypotheses for the length 10 sequences of Experiment 2B (Panel A, B, and C). Panel D displays the observed data.
Figure 4.3. Error shift predictions from three hypotheses for the length 13 sequences of Experiment 2B (Panel A, B, and C). Panel D displays the observed data. (Note these predictions for length 13 are the inverse of those for location 10 in Figure 4.2.)
Figure 4.4. WMs for each frequency pattern (F_A and F_B) as a function of length for Experiment 2A (constant intensity).
Figure 4.5. WMs as a function of length, for the congruent (Panel A) and incongruent frequency/intensity patterns (Panel B) of Experiment 2B.
In speech and music, although intensity changes often come in the form of continuous changes in loudness over time, they also appear in the form of discrete accent patterns. The commonly used musical terms of crescendo and decrescendo refer respectively to gradual and uniform increases and decreases in intensity over time. Accenting, on the other hand, refers to discrete serial changes in intensity (or some other dimension). Experiments 1 and 2 examined intensity changes that simulate dynamic changes in an auditory (music-like) sequence. Experiment 3 and 4 examine discrete intensity changes that simulate intensity accent patterns. All of the stimuli used in Experiment 2 can be described as highly coherent, in that the sequences have predictable frequency and intensity structure and are rhythmically simple. And it was shown in Experiment 2 that periodic changes in frequency and intensity, that imply increasing and decreasing pitch and/or loudness, can affect pitch judgment errors in this task. Although these sequences do approximate the structure of some sound patterns that listeners normally encounter, music, for instance, often contains intensity accents instead of (or in addition to) gradual intensity changes.

It is the goal of Experiment 3 to investigate whether intensity accent patterns within a periodic frequency pattern can influence pitch judgments. Therefore, in this experiment loudness patterns are created by adding regularly occurring intensity accents
to the periodic frequency patterns used in Experiment 2, as shown in Figure 5.1. As opposed to a graduated series of changes, an accent reflects a prominent and singular discrete serial change along a dimension, such as frequency, duration, or in this case intensity. Thus, instead of a higher-order pattern of gradually increasing and decreasing intensities, evocative of crescendo and decrescendo patterns in music, Experiment 3 considers intensity patterns based on only two discrete levels that lead to accentuation patterns in music. Two intensity levels correspond, respectively, to the lowest and highest dB values used in Experiments 1 and 2. Furthermore, by the reasoning established earlier, an intensity accent pattern is deemed congruent with the frequency pattern when louder tones (accents) occur at frequency peaks in the sequence; conversely, an intensity accent pattern is incongruent with the frequency pattern when intensity accents occur at frequency troughs in the sequence. This is shown in Table 5.1. In addition, in this experiment the pattern of intensity accents follows (reinforces) the up/down frequency patterns of these sequences and hence it is characterized by regular timing. Specifically, accents only occur at period boundaries. Therefore, all of the stimuli used in Experiment 3 can be described as highly coherent, in that the sequences have predictable frequency and intensity structure and are rhythmically simple. Subsequently, the coherence of the induction sequence is manipulated by varying the timing of these accents, i.e., in Experiment 4 (detailed in Chapter 6).

In Experiment 1, which employed monotonic frequency and intensity changes, error shifts were decreased when frequency and intensity changes were incongruent versus congruent. In Experiment 2, which employed periodic frequency and intensity changes, similar evidence was also found, however only in one condition, i.e., smaller
WMs for incongruent F_{AiB} patterns compared to congruent F_{AiA} at length 10. Experiment 3 considers whether pitch judgments are similarly affected by the occurrence of congruent versus incongruent intensity accent patterns, as compared to the congruent and incongruent graduated intensity changes of Experiment 2.

Two hypotheses investigated in Experiment 2 are also relevant to Experiment 3; these are the pattern-based expectancy hypothesis and the pattern congruency hypothesis. Again, the primary measure used to evaluate these hypotheses is a weighted measure (WM), plus overall accuracy will also be examined. It should be noted that also in this experiment error shifts for length 10 sequences provide a critical test of these hypotheses. WM results at this period boundary will indicate whether listeners are focused on the higher or lower-order frequency pattern and whether error shifts are modulated by congruency. Once again, error shifts for length 13 sequences will also be examined, despite the fact that listeners know the induction sequence will never be longer than 13 tones and therefore may be biased toward lower-order pattern structure.

Predictions from the two hypotheses are graphically depicted in Figure 5.2 (Panel A and B) for length 10 sequences, and Figure 5.3 (Panel A and B) for length 13 sequences. Predictions parallel those made for Experiment 2, as discussed in Chapter 4. In brief, the pattern-based expectancy hypothesis predicts that WM s will be consistent with continuation of the experienced higher-order frequency pattern\(^{11}\); and even though the intensity accents may be perceived as a coherent pattern, this hypothesis makes no

\(^{11}\) The predicted direction and magnitude of WM s is based on the results of Johnston and Jones (in press) who found that error shifts were large and reversed at period boundaries. However, according to Verfaillie and d’Ydewalle (1991) evidence of attending to the higher-order pattern is also obtained when WM s at a period boundary are close to zero.
explicit predictions regarding how intensity will influence pitch judgments. Alternatively, the *pattern congruency hypothesis* predicts that WMs will be consistent with continuation of the experienced higher-order frequency pattern; and even though the intensity accents are task-irrelevant, the magnitude of WMs will be greater when the intensity accent pattern is congruent with the frequency pattern (accents on frequency peaks) and smaller when the intensity accent pattern is incongruent with the frequency pattern (accents on frequency troughs).

**Methodology**

*Subjects.* Fifty-eight undergraduate students with normal hearing and fewer than ten years of formal musical training (mean = 1.6 years) participated in this experiment in exchange for credit in the introductory psychology course at The Ohio State University. The data from five participants were discarded, four participants responded to fewer than 80% of trials and one participant responded to more than 80% of trials however the trials s/he missed included all presentations of certain unique patterns resulting in missing data.

*Apparatus.* All equipment used was identical to the rating experiment.

*Stimuli.* All experimental patterns were identical to sequences used in Experiment 2B except the intensity variable was changed. Instead of having intensity patterns that increased and decreased periodically, certain accented tones were loud (79 dB), whereas all others were a constant lower intensity (65.5 dB). To create sequences with regular accent timing, tones were accented according to the location of peak intensities in the $I_A$ and $I_B$ patterns from Experiment 2. That is, for an $I_A$ sequence, tones 1, 7, and 13 (when present) were 79 dB and all other tones were 65.5 dB, see Panel A of Figure 5.1. For an
IB sequence, tones 4 and 10 were 79 dB and all other tones were 65.5 dB, see Panel B of Figure 5.1.

Design. The design of Experiment 3 is diagrammed in Table 5.1, where the arrows symbolize frequency direction and the circles symbolize intensity accents. Note that congruent patterns are those with intensity accents at frequency peaks. The two types of frequency patterns, FA and FB, served as a between subjects variable (n = 26 and 27, respectively). Within subjects variables included intensity accent pattern of the induction sequence (congruent and incongruent), length of the induction sequence (10, 11, 12, and 13 tones), frequency range (low and high), and frequency shift of the probe tone (-70 c, -35 c, 0 c, +35 c, and +70 c). This resulted in a 2 x (2 x 4 x 2 x 5) mixed factorial design, and a total of 160 unique sequences. In each group, listeners heard half of the 80 patterns associated with a particular frequency pattern (FA and FB) three times and the other half of the 80 patterns two times.

Procedure. Same as Experiment 2.

Dependent Measures. Same as Experiment 1 and 2.

Results

Table 5.2 presents the average WM and PC scores for each frequency pattern (FA and FB) as a function of intensity accent pattern (congruent and incongruent) and sequence length, collapsed over the frequency range variable, for all conditions in Experiment 3. In addition, Figure 5.4 displays WMs for each frequency pattern as a function intensity accent pattern and sequence length, collapsed over the frequency range variable.
**WM analyses**

A mixed ANOVA was conducted using WMs, with frequency pattern as a between subjects variable and congruency, sequence length, and frequency range as within subjects variables. This revealed a significant interaction of frequency pattern with congruency, \( F(1, 51) = 4.17, MSe = 174.73, p < .05 \). Specifically, the absolute magnitudes of error shifts were greater with congruent patterns (\( F_{AI} \) WM = -1.79 and \( F_{BI} \) WM = +3.38) versus incongruent patterns (\( F_{IA} \) WM = -0.72 and \( F_{IB} \) WM = +0.74).

There was also a significant interaction of frequency pattern with sequence length, \( F(3, 153) = 5.20, MSe = 285.32, p = .002 \). The observed WMs for this interaction are presented in Table 5.3. Trend analyses revealed a significant linear trend over sequence length with the \( F_A \) pattern \( [F(1, 51) = 5.68, MSe = 402.53, p = .02; F_B: p = .12] \), along with a significant difference between the \( F_A \) and \( F_B \) patterns \( [F(1, 51) = 7.94, MSe = 402.53, p = .007] \). Similar to the findings of Experiment 2A and 2B, these results suggest that the higher-order frequency pattern influences pitch discrimination at period boundaries. WMs at length 10 and 13 period boundaries are reversed (\( F_A \) length 10 and 13, \( F_B \) length 13) and/or close to zero (length 10 \( F_A \) and \( F_B \)). These results can be interpreted as consistent with both the pattern-based expectancy and pattern congruency

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12 With length 10 \( F_B \) patterns, it is unclear whether higher or lower-order structure influenced pitch judgments. The WM indicates a small error shift toward higher probes (WM = +1.71), and because \( F_B \) patterns rise in frequency up to tone 10 this may be evidence that lower-order structure influenced responding. However, when compared to the linearly increasing sequences of Experiment 1A (WM = +8.40), WMs with the length 10 \( F_B \) sequences of Experiment 3 seem greatly reduced, indicating that higher-order structure may have influenced judgments.
hypotheses, as they predict that error shifts at period boundaries should reflect continuation of the higher-order frequency pattern.

The interaction of frequency pattern with sequence length was significant, however this was not qualified by congruency. That is, the three way interaction of frequency pattern, congruency, and sequence length was not significant, $p = .81$. Thus, congruency of frequency and intensity did not differentially increase (or decrease) the magnitude of errors at certain locations in the pattern. The relevant WMs are displayed in Figure 5.4 and Table 5.2. Planned comparisons conducted to test for an interaction of frequency pattern and congruency at period boundaries confirmed that no significant differences were present. And finally, for each frequency pattern, planned comparisons were conducted to investigate whether the magnitude of WMs differed for congruent versus incongruent patterns at period boundaries. Again, no significant differences were found.

The major point of interest in this experiment concerns differences in WMs based on frequency pattern and congruency at the critical length 10 period boundary. Figure 5.2 Panel C graphically displays the observed data, along with the predictions from the two hypotheses under consideration (Panels A and B). Error shifts at this location offer a clear test of the predictions from the pattern-based expectancy and pattern congruency hypotheses. In examining the observed data, the pattern of WMs indicates that listeners are focused on the higher-order frequency pattern. WMs are all very close to zero, which is consistent with continuation of the higher-order frequency pattern (Verfaillie & d’Ydewalle, 1991); this is because if listeners rely only on lower-order structure, with monotonic sequences, then error shifts (WMs) should be large and in the direction
consistent with the immediately preceding trajectory. Despite the fact that the WMs are not as large as the values observed for the comparable patterns in Experiment 2A (which contained no intensity changes), these results are consistent with the pattern-based expectancy hypothesis, which predicts that error shifts will be consistent with the higher-order pattern and which provides no explicit predictions regarding the influence of intensity patterns.

In addition, WMs at length 13 are also considered. Panel C of Figure 5.3 graphically displays the observed data, along with the predictions from the two hypotheses under consideration (Panels A and B). In examining the observed data, the pattern of WMs indicates that listeners are focused on the higher-order frequency pattern and that WMs are modulated by congruency. These results exactly match predictions from the pattern congruency hypothesis. Despite the fact that this location is confounded by the listeners’ knowledge that the sequence will not continue, errors were clearly influenced by congruency within the higher-order pattern.

The overall ANOVA also revealed two significant effects related to the frequency range variable. There was a significant main effect of frequency range \( F (1, 51) = 5.08, MSe = 181.50, p = .03 \) and a significant interaction of sequence length with frequency range \( F (3, 153) = 12.52, MSe = 196.10, p < .001 \). The WMs for the two way interaction are displayed in Table 5.4. Tukey HSD post hoc tests indicated that at both lengths 11 and 12, WMs for low and high frequency range sequences differed significantly. Essentially, listeners were more likely to respond ‘same’ to lower probes with low frequency range patterns and to higher probes with high frequency range
patterns. These differences, however, did not interact with frequency pattern or congruency.

**Experiment 3 vs. Experiment 2B.** Analyses were also conducted to investigate whether varying intensity gradually, as in Experiment 2B, influenced pitch judgments differently from when intensity patterns were created with accents, as in Experiment 3. A mixed ANOVA was conducted comparing the WM results of Experiment 2B to the results from Experiment 3. Therefore, experiment and frequency pattern were between subjects variables and congruency, sequence length, and frequency range were within subjects variables. This revealed three significant sources of variance. There was a main effect of experiment \( F(1, 106) = 7.19, MSe = 777.44, p = .01 \), an interaction of experiment with frequency pattern \( F(1, 106) = 7.03, MSe = 777.44, p = .01 \), and an interaction of experiment with frequency pattern and congruency \( F(1, 106) = 4.47, MSe = 146.69, p = .04 \). The three way interaction is displayed in Table 5.5. Tukey HSD post hoc tests revealed a significant difference between WMs with the congruent FAIA sequence in Experiment 2B (WM = +7.13) compared to Experiment 3 (WM = -1.79). This significant difference is likely attributable to the fact that in Experiment 2B large positive WMs occur at length 10 (see Figure 4.5 Panel A) and in Experiment 3 large negative WMs occur at length 13 (see Figure 5.4 Panel A). Although error shifts at period boundaries in both experiments reflected that listeners were attending to the higher-order frequency pattern, in Experiment 2B the magnitude of WMs was greatest at length 10 and in Experiment 3 the magnitude of WMs was greatest at length 13.

In summary, in Experiment 3, error shifts were generally consistent with continuation of the higher-order frequency pattern regardless of intensity accent pattern.
This finding is consistent with those reported in Experiment 2. More importantly, three effects of congruency were found in Experiment 3, where intensity was varied in large discrete steps. First, the absolute magnitudes of error shifts were greater within patterns where intensity accents were congruent than in ones where they were not. Second, at the length 13 period boundary WMs reflected an anticipated continuation of the higher-order frequency pattern and these error shifts were modulated by congruency. Specifically, congruent patterns had larger absolute WMs than incongruent patterns (see Panel C of Figure 5.3). This suggests that listeners were extrapolating the higher-order frequency pattern past a known ending point more with congruent than with incongruent sequences. Third, listeners were also focused on the higher-order frequency pattern at length 10 according to WM scores at this boundary point; however, by contrast, here all WM values were small and did not vary with congruency.

PC analyses

A mixed ANOVA was conducted using PC data, with frequency pattern as a between subjects variable and congruency, sequence length, and frequency range as within subjects variables. This revealed several main effects and interactions associated with frequency pattern, congruency, and sequence length. There was a main effect of congruency $[F (1, 54) = 11.08, MSe = 0.03, p = .001]$, with greater accuracy for congruent patterns (PC = .66) compared to incongruent patterns (PC = .64). There was also a main effect of sequence length $[F (3, 162) = 3.92, MSe = 0.10, p < .001]$, with lower accuracy at the period boundaries (length 10 PC = .59; length 13 PC = .58) compared to higher accuracy at lengths 11 (PC = .71) and 12 (PC = .73), Tukey HSD ($p < .05$). These effect were qualified by significant interactions of frequency pattern with
congruency \[ F (1, 54) = 4.26, \textit{MSe} = 0.03, \textit{p} = .04 \], frequency pattern with sequence length \[ F (3, 162) = 3.92, \textit{MSe} = 0.10, \textit{p} = .01 \], and frequency pattern with congruency and sequence length \[ F (3, 162) = 23.98, \textit{MSe} = 0.05, \textit{p} < .001 \]. The PC values for this three way interaction are displayed in Table 5.2. Tukey HSD post hoc tests revealed two significant differences. First, with length 10 \( F_A \) patterns, accuracy was higher for congruent (PC = .66) versus incongruent (PC = .53) patterns. Second, with length 13 \( F_B \) patterns, accuracy was also higher for congruent (PC = .64) versus incongruent (PC = .47) patterns. Examining the structure of these four sequences, with the incongruent length 10 \( F_A \) and length 13 \( F_B \) patterns the last induction sequence tone contains an intensity accent whereas the congruent versions do not. Furthermore, taking a closer look at accuracy, the lowest PC values are obtained when the final induction sequence tone is an intensity accent, length 10 \( F_A I_B \) (PC = .53), length 10 \( F_B I_B \) (PC = .55), length 13 \( F_A I_A \) (PC = .57), and length 13 \( F_B I_A \) (PC = .47). It seems that regardless of whether the frequency and intensity pattern of the induction sequence is congruent or incongruent, performance is poor when the final induction sequence tone is an intensity accent. However, it should be noted that a comparable affect of final intensity level on WMs was not observed.

\textit{Discussion}

In Experiment 3, error shifts were generally consistent with continuation of the higher-order, and not the lower-order, frequency pattern. The significant frequency pattern and sequence length interaction and the observed WMs at both length 10 and 13 period boundaries support this. More importantly, there were also several effects
attributable to congruency. First, the absolute magnitudes of error shifts were greater with congruent patterns than with incongruent patterns. This result agrees with similar results from Experiment 1B and 2B, where WMs were greater for congruent versus incongruent patterns. Second, at the length 13 period boundary WMs reflected continuation of the higher-order frequency pattern and the magnitude of WMs were larger for congruent versus incongruent patterns. At length 10, WMs indicated that listeners were also focused on the higher-order frequency pattern, however WM values were small and did not vary with congruency.

These results shed some light on predictions from two hypotheses as presented in Figures 5.2 and 5.3. Given the structure of these periodic patterns, the length 10 period boundary continues to offer the clearest test of these hypotheses in Experiment 3. Panel C of Figure 5.2 graphically displays the observed WMs at length 10 which can be compared with predictions from the two hypotheses under consideration (Panels A and B). In addition, WMs at length 13, which would also serve as a period boundary if the sequence were to continue, can also be considered. These results are displayed in Panel C of Figure 5.3 and can be compared with predictions from the two hypotheses (Panels A and B).

First, the pattern-based expectancy hypothesis correctly predicts an interaction of frequency pattern with sequence length, with errors shifted in the direction consistent with continuation of the experienced higher-order periodic frequency pattern. Considering the critical length 10 period boundary, WMs for both congruent and incongruent patterns are similar and close to zero, suggesting anticipation of the higher-order frequency pattern. One possible exception is with the congruent F_Bl_B pattern, where tone 10 is a frequency peak. The magnitude of the WM is moderate (+2.81) and shifted
toward higher probes, which could be consistent with continuation of the lower-order
frequency trajectory. However, when this WM is compared to WMs with the linearly
increasing sequence of Experiment 1A (WM = +8.40), it seems greatly reduced.
Considering the length 13 period boundary, the WMs clearly show that the higher-order
frequency pattern influenced errors for both congruent and incongruent patterns. These
results agree with the pattern-based expectancy hypothesis, however this approach cannot
account for why, at length 13, error shifts were smaller with incongruent patterns and
larger with congruent patterns.

The pattern congruency hypothesis assumes that when an intensity pattern is
congruent with a frequency pattern, it will be difficult for listeners to ignore intensity
variations even though they are irrelevant in this experiment. Conversely, this bias is
reduced when irrelevant intensity variations form an incongruent pattern. Therefore, this
hypothesis makes two predictions. First, it correctly predicts that errors will be shifted in
the direction consistent with continuation of the higher-order frequency pattern. Second,
it predicts that the absolute magnitude of error shifts will be relatively greater with
congruent than incongruent patterns, because with congruent patterns the irrelevant
dimension reinforces the relevant frequency pattern and with incongruent patterns the
irrelevant dimension does not. This predicted congruency effect was also obtained,
however only with length 13 patterns. This hypothesis provides a better account of the
observed data as compared to predictions from the pattern-based expectancy hypothesis,
however this approach cannot account for why, at length 10, no congruency effects were
obtained.
Summary

The main goal of Experiment 3 was to investigate how pitch judgments of a probe tone are influenced by including temporally regular intensity accent patterns in the periodic increasing and decreasing frequency patterns that comprise the induction sequences. The results of this experiment revealed that intensity accent patterns can influence pitch perception, but the effects are not dramatic. Generally, error shifts reflected continuation of the higher-order frequency pattern regardless of the intensity accent pattern. The influences of the intensity accent manipulation are confined to a few isolated variations associated with pattern congruency. First, there was an overall effect of congruency, with greater error shifts with congruent versus incongruent patterns. Second, these congruency effects were pronounced at the length 13 period boundary (but not at length 10). WMs for length 13 sequences reflected continuation of the higher-order frequency pattern (past the pattern’s known ending) and the magnitude of WMs was larger for congruent than for incongruent patterns. An additional finding was that accuracy (PC) was affected by intensity level. Specifically, at both period boundaries (10 and 13), PC was lower when the final induction sequence tone was an intensity accent versus when it was unaccented.

The pattern-based expectancy hypothesis correctly predicted that error shifts would reflect the higher-order frequency pattern, however it cannot account for the congruency effect found at the length 13 period boundary. The pattern congruency hypothesis was the most successful hypothesis. It correctly predicted that errors would reflect the higher-order frequency pattern and it correctly predicted the congruency effect
found at the length 13 period boundary. However, it cannot account for why a similar congruency effect was not found at length 10.
Table 5.1. The frequency patterns (arrows) and intensity accent patterns (circles) in Experiment 3 induction sequences.
| Frequency | Intensity     | Length  
|-----------|--------------|---------
|           |              | 10      | 11      | 12      | 13      |
| FA        | Congruent (I_A) | +1.58 (.66) | -0.03 (.66) | -3.35 (.71) | -5.34 (.57)* |
|           | Incongruent (I_B) | +1.66 (.53)* | +0.66 (.69) | -1.74 (.69) | -3.48 (.63) |
| FB        | Congruent (I_B) | +2.81 (.55)* | -1.41 (.79) | +6.82 (.76) | +5.31 (.64) |
|           | Incongruent (I_A) | +0.61 (.64) | -2.75 (.71) | +2.18 (.75) | +2.89 (.47)* |

Table 5.2. WMs for each frequency pattern, as a function of intensity pattern and sequence length, in Experiment 3. PC scores are inside parentheses. 
"*" indicates locations of intensity accents.
<table>
<thead>
<tr>
<th>Frequency</th>
<th>10</th>
<th>11</th>
<th>12</th>
<th>13</th>
</tr>
</thead>
<tbody>
<tr>
<td>( F_A )</td>
<td>+1.62</td>
<td>+0.32</td>
<td>-2.54</td>
<td>-4.41</td>
</tr>
<tr>
<td>( F_B )</td>
<td>+1.71</td>
<td>-2.08</td>
<td>+4.50</td>
<td>+4.10</td>
</tr>
</tbody>
</table>

Table 5.3. WM for the significant frequency pattern and sequence length interaction in Experiment 3.
<table>
<thead>
<tr>
<th>Frequency Range</th>
<th>10</th>
<th>11</th>
<th>12</th>
<th>13</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low</td>
<td>+3.40</td>
<td>-4.91</td>
<td>-2.97</td>
<td>+1.91</td>
</tr>
<tr>
<td>High</td>
<td>-0.07</td>
<td>+3.14</td>
<td>+4.93</td>
<td>-2.22</td>
</tr>
</tbody>
</table>

Table 5.4. WMs for the significant sequence length and frequency range interaction in Experiment 3.
Frequency Pattern

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Intensity Accent Pattern</th>
<th>$F_A$</th>
<th>$F_B$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2B</td>
<td>Congruent ($I_A$)</td>
<td>+7.13</td>
<td>+2.80</td>
</tr>
<tr>
<td></td>
<td>Incongruent ($I_B$)</td>
<td>+4.56</td>
<td>+1.40</td>
</tr>
<tr>
<td>3</td>
<td>Congruent ($I_B$)</td>
<td>-1.79</td>
<td>+3.38</td>
</tr>
<tr>
<td></td>
<td>Incongruent ($I_A$)</td>
<td>-0.72</td>
<td>+0.74</td>
</tr>
</tbody>
</table>

Table 5.5. WM for the significant interaction of experiment (Experiment 2B versus 3) with frequency pattern and congruency.
Figure 5.1. Example of a 13 tone induction sequence, followed by a probe tone (hatched circle), from Experiment 3. Panel A: the congruent \(F_A I_A\) pattern and Panel B: the incongruent \(F_A I_B\) pattern. Filled circles represent intensity accents in the sequence.
Figure 5.2. Error shift predictions from two hypotheses for the length 10 sequences of Experiment 3 (Panel A and B). Panel C displays the observed data.
Figure 5.3. Error shift predictions from three hypotheses for the length 13 sequences of Experiment 3 (Panel A and B). Panel C displays the observed data.
Figure 5.4. WMs as a function of length, for the congruent (Panel A) and incongruent frequency/intensity patterns (Panel B) of Experiment 3.
The sounds that listeners encounter on a daily basis are complex, changing dynamically in various ways in time. Often these sound patterns are highly coherent, in that they have predictable frequency and intensity structure and are rhythmically simple. However, irregular variation within the dimensions of frequency, intensity and/or time can lead to sound patterns that are less coherent in time. All of the stimuli used in Experiment 3 were highly coherent, and it was found that intensity accent patterns did affect pitch perception. It is possible that the incorporation of temporally regular intensity accent patterns within these periodic frequency patterns reinforced the higher-order frequency pattern. If so, it is also possible that creating a less coherent pattern by including temporally irregular intensity accents within these same frequency patterns may have a different effect on pitch perception.

It is the goal of Experiment 4 to investigate whether temporally irregular accents within the induction sequence affect errors in a different manner as compared to the regularly timed intensity accents in Experiment 3. In Experiment 4, loudness patterns are created by adding randomly occurring intensity accents to the periodic frequency patterns used in Experiments 2 and 3, as shown in Figure 6.1. Specifically, the induction sequences in Experiment 4 contain intensity accents that can be congruent or incongruent with frequency at sequence length 10 or 13; however, earlier accents in the induction
sequences occur at random locations that do not coincide with period boundaries. This is shown in Table 6.1. It is possible that adding temporally irregular intensity accents to these periodic frequency patterns may be relatively disruptive. Compared to the sequences in Experiment 3, here all intensity accents in a sequence will not necessarily coincide with frequency peaks or troughs to create perfectly congruent or incongruent patterns. In addition, in Experiment 3 the relative timing of intensity accents was uniform, every 7 tones; however, in Experiment 4 such invariant timing is missing. As a result, if attending is facilitated or dependent on temporal coherence of accents, then attentional tracking may be more sporadic when these accents are irregularly timed. This would be especially true if listeners cannot ignore task-irrelevant variations of intensity. In this case, irregular intensity accents should disrupt attending to higher-order pattern structure. One consequence of this might be to force listeners to focus more on the lower-order, instead of the higher-order, frequency trajectory. Alternatively, it is possible that the temporal irregularity of the intensity accents will enable listeners to ignore intensity variations entirely. In this case, listeners may continue to focus on the higher-order frequency pattern, with pitch judgments showing no effects of intensity.

The two hypotheses investigated in Experiment 3 continue to be relevant to Experiment 4; these are the pattern-based expectancy hypothesis and the pattern congruency hypothesis. First, error shift predictions from the pattern-based expectancy hypothesis appear in Figure 6.2 (Panel A) for the length 10 period boundary and in Figure 6.3 (Panel A) for the length 13 period boundary. This hypothesis assumes that, with a temporally predictable pattern, attention will be targeted in time to when the next event will occur and what that next event will be, e.g., it’s pitch. However, considering the
structure of the intensity accents used in this experiment, it is possible that the irregularly
timed intensity accents will result in a relatively incoherent pattern. As a result, the
periodic frequency changes may seem less pattern-like because the regular time intervals
between frequency period boundaries do not match the irregular time intervals that obtain
between intensity accents. If this occurs, attending to the higher-order frequency pattern
may be disrupted and listeners will focus more on the lower-order frequency trajectory
that immediately precedes the probe tone, instead of the higher-order frequency pattern.
In support of this prediction is evidence, provided by Jones and Yee (1997), that
irregularity of higher-level intensity accents does disrupt attentional tracking of sound
patterns. Based on these assumptions, the pattern-based expectancy hypothesis predicts
that the direction of WMs at the period boundaries will reflect continuation of the lower-
order (linear) frequency trajectory.

Predictions from the pattern congruency hypothesis appear in Panel B of Figures
6.2 and 6.3. In Experiment 2, this approach assumed that when a constantly changing
intensity pattern is congruent with a frequency pattern, it is difficult for listeners to ignore
the irrelevant intensity variations. With respect to temporally regularly intensity accents
(Experiment 3), the same general proposal regarding the reinforcing aspects of congruent
intensity and frequency patterns holds. However, in this experiment the temporally
irregular intensity accent patterns are not entirely congruent or incongruent with the
periodic frequency pattern. That is, accents in a sequence do not always occur at
frequency peaks, to form congruent patterns, or always at frequency troughs, to form
incongruent patterns. As a result, the temporally irregular intensity accents may not
contribute to forming a compelling integrated pattern and they may not conflict with the
periodic frequency pattern. Instead, the structure of these intensity accents may allow
listeners to completely ignore the irrelevant intensity variations. Essentially, attention will
continue to be targeted toward continuation of the relevant frequency pattern and the
irrelevant intensity accents will be ignored. Based on these assumptions, a pattern
congruency approach predicts that listeners will focus on the higher-order frequency
pattern; and the direction of WMs at the period boundaries will reflect continuation of the
periodic frequency pattern.

Methodology

Subjects. Sixty-three undergraduate students with normal hearing and fewer than
ten years of formal musical training (mean = 2.0 years) participated in this experiment in
exchange for credit in the introductory psychology course at The Ohio State University.
The data from five participants were discarded, one participant responded to fewer than
80% of trials, three participants responded to more than 80% of trials however the trials
they missed included all presentations of certain unique patterns resulting in missing data,
and one participant’s overall accuracy was less than 30%.

Apparatus. All equipment used was identical to the rating experiment.

Stimuli. All experimental patterns were identical to sequences used in Experiment
3, except the intensity variable was changed. Instead of intensity accents occurring at
period boundaries, the location of these accents occurred randomly from trial to trial. To
create sequences with irregular intensity accent timing, intensity accent patterns were
adapted from I_A and I_B patterns, however only the accent structure of tones 10 to 13
stayed the same as the I_A and I_B patterns. The location of other intensity accents, earlier in
the sequence, randomly varied with the constraint that the location was never at a period boundary. Thus, an IA sequence in this experiment refers to a sequence that always contains an intensity accent at tone 13 (when present) and which also has intensity accents at either serial position 2 or 3 and at either serial position 5, 6, 8 or 9. IB sequences always contain an intensity accent at tone 10 and also one intensity accent at either serial position 2, 3, 5, or 6. All possible combinations of intensity accent locations occurred equally often and were randomly assigned to each unique sequence length/frequency range/probe sequence. Considering only tones 10 and 13, intensity accents co-occur with a frequency peak for FAIA and FBIB patterns; because louder sounds here are paired with higher frequencies, these sequences will still be referred to as congruent. Conversely, intensity accents co-occur with a frequency trough for FABI and FIBI; because louder sounds here are paired with lower frequencies, these sequences will still be referred to as incongruent.

Design. The design of Experiment 4 is diagrammed in Table 6.1, where arrows symbolize frequency direction and circles symbolize intensity accents. The two types of frequency patterns, FA and FB served as between subjects variables, (n = 26 and 32, respectively). Within subjects variables included final intensity accent (congruent and incongruent), length of the induction sequence (10, 11, 12, and 13 tones), frequency range (low and high), and frequency shift of the probe tone (-70 c, -35 c, 0 c, +35 c, and +70 c). This resulted in a 2 x (2 x 4 x 2 x 5) mixed factorial design, and a total of 160 unique sequences. In each group, listeners heard half of the 80 patterns associated with a particular frequency pattern (FA and FB) three times and the other half of the 80 patterns two times.
Procedure. Same as Experiments 2 and 3.

Dependent Measures. Same as Experiments 1, 2, and 3.

Results

Table 6.3 presents the average WM and PC scores for each frequency pattern (F_A and F_B) as a function of final intensity accent (congruent and incongruent) and sequence length, collapsed over the frequency range variable, for all conditions in Experiment 4. In addition, Figure 6.4 displays WMs for each frequency pattern as a function of final intensity accent and sequence length, collapsed over the frequency range variable.

WM analyses

A mixed ANOVA was conducted using WMs, with frequency pattern as a between subjects variable and final intensity accent, sequence length, and frequency range as within subjects variables. This revealed a main effect of frequency pattern \([F (1, 56) = 5.41, MSe = 1090.12, p = .02]\), which was qualified by a significant interaction of frequency pattern with sequence length \([F (3, 168) = 9.05, MSe = 341.46, p < .001]\). The WMs for this interaction are displayed in Table 6.3. Trend analyses revealed significant linear trends over sequence length with both F_A and F_B frequency patterns \([F_A: F (1, 56) = 10.67, MSe = 412.87, p = .002; F_B: F (1, 56) = 10.87, MSe = 412.87, p = .002]\), along with a significant difference between these trends \([F (1, 56) = 21.47, MSe = 412.87, p < .001]\). These results suggest that the higher-order frequency pattern influences pitch judgments at period boundaries. WMs at both length 10 and 13 period boundaries are reversed. These results can be interpreted as consistent with predictions from the pattern congruency hypothesis. This approach predicted that error shifts at period boundaries...
would reflect continuation of the higher-order frequency pattern. Conversely, the pattern-based expectancy approach incorrectly predicted that error shifts would reflect continuation of the lower-order frequency trajectory.

Results of the ANOVA indicated that there were no significant main effects or interactions associated with congruency of the final intensity accent in this experiment. Thus, whether the frequency pattern and the final intensity accent were congruent or not, did not differentially increase (or decrease) the magnitude of errors at certain locations in the pattern. The relevant WMs are displayed in Figure 6.4 and Table 6.2.

A point of interest in this experiment concerns differences in WMs based on congruency between the frequency pattern and the final intensity accent. In previous experiments, the pattern congruency hypothesis has predicted that the magnitude of WMs would be greater for congruent than for incongruent patterns. However, in this experiment the intensity variations do not form a temporally coherent congruent or incongruent pattern. For this reason, the pattern congruency hypothesis predicts that there should be no reliable effects of intensity on error shifts. Panel C of Figures 6.2 and 6.3 graphically display the observed WMs for length 10 and 13 sequences respectively. These results can be compared with predictions from the two hypotheses under consideration (Panels A and B). Consistent with the pattern congruency hypothesis, the results suggest that listeners in this experiment are focused on the higher-order frequency pattern and that error shifts are not modulated by congruency of the probe tone. WMs at length 10 and 13 period boundaries are reversed and/or close to zero.

The overall ANOVA also revealed a significant interaction of sequence length with frequency range [$F(3, 168) = 12.47, MSe = 270.68, p < .001$]. The WMs for this
interaction are displayed in Table 6.4. Tukey HSD post hoc tests \( (p < .05) \) indicated that at lengths 11, 12, and 13, WMs for low and high frequency range sequences differed significantly. Essentially, listeners were more likely to respond ‘same’ to lower probes with low frequency range patterns and to higher probes with high frequency range patterns for lengths 11 and 12, and the opposite obtained at length 13. These differences, however, did not interact with frequency pattern or congruency.

**Experiment 4 vs. Experiment 3.** Analyses were conducted to investigate whether a regular intensity accent pattern (Experiment 3) versus a temporally irregular intensity accent pattern (Experiment 4) influenced pitch judgment errors differently. A mixed ANOVA was conducted comparing the WM results of Experiment 4 to the results from Experiment 3. Therefore, experiment and frequency pattern were between subjects variables and congruency, sequence length, and frequency range were within subjects variables. This revealed no effects of experiment. Regardless of whether intensity accent patterns were regular or irregular, WMs were similar in both experiments.

In summary, the results of Experiment 4 indicate that the higher-order frequency pattern influenced pitch judgments at period boundaries. The intensity variations in this experiment seemed to have no effect on error shifts. The results suggest that listeners were able to ignore the temporally irregular intensity accent patterns, as instructed.

**PC Analyses**

A mixed ANOVA was conducted using PC data, with frequency pattern as a between subjects variable and final intensity accent (congruent or incongruent), sequence length, and frequency range as within subjects variables. This revealed a main effect of sequence length \( [F (3, 174) = 24.28, MSe = 0.08, p < .001] \), with lower accuracy at the
period boundaries (length 10 PC = .60; length 13 PC = .62) compared to higher accuracy at lengths 11 (PC = .70) and 12 (PC = .73), Tukey HSD (p < .05). These effect were qualified by a significant interaction of frequency pattern with final intensity accent and sequence length \([F (3, 174) = 29.67, MSe = 0.05, p < .001]\). The PC values for this three way interaction are displayed in Table 6.2. Tukey HSD post hoc tests revealed three significant differences. First, with length 10 FA patterns, accuracy was higher for \(F_AI_A\) sequences (PC = .69) versus \(F_AI_B\) sequences (PC = .56). Second, with length 13 FB patterns, accuracy was also higher for \(F_BI_B\) sequences (PC = .66) versus \(F_BI_A\) sequences (PC = .50). Third, with length 10 FB patterns, accuracy was higher for \(F_BI_A\) sequences (PC = .63) versus \(F_BI_B\) sequences (PC = .52). Examining the structure of these six patterns, with the sequences that yielded lower accuracy, the last induction sequence tone co-occurred with an intensity accent whereas the sequences that yielded greater accuracy did not. Furthermore, all the lowest PC values are obtained when the final induction sequence tone is an intensity accent, length 10 \(F_AI_B\) (PC = .56), length 10 \(F_BI_B\) (PC = .52), length 13 \(F_AI_A\) (PC = .63), and length 13 \(F_BI_A\) (PC = .50). It seems that regardless of whether the frequency pattern and final intensity accent is congruent or not, performance is poor when the final induction sequence tone in an intensity accent. However, it should be noted that a comparable affect of final intensity level on WMs was not observed.

**Experiment 4 vs. Experiment 3.** Planned comparisons were conducted to investigate whether varying intensity with irregular intensity accent patterns (Experiment 4) facilitated or inhibited pitch judgments relative to performance with the regular intensity accent patterns of Experiment 3. A mixed ANOVA comparing Experiment 4 with Experiment 3 found no significant main effects or interactions. Accuracy was
essentially equivalent across all conditions with average PCs of .67 for Experiment 4 and .65 for Experiment 3.

In summary, there were effects of intensity on accuracy (PC) within Experiment 4. Specifically, at the length 10 and 13 period boundaries, accuracy was lower when the final induction sequence tone was an intensity accent versus when it was not an accent. This effect of final intensity on accuracy was also found in Experiment 1B and 3.

Discussion

In Experiment 4 error shifts were consistent with continuation of the higher-order, and not the lower-order, frequency pattern. The significant frequency pattern and sequence length interaction and the observed WMs at both length 10 and 13 period boundaries support this. In addition, no significant effects of final intensity accent (congruent or incongruent) on error shifts were found in this experiment. It is significant and revealing that the observed WMs most closely resembled the results of Experiment 2A where the frequency patterns contained no intensity variations.

These results shed some light on the way in which listeners rely on patterns to generate expectancies that in turn bias pitch judgments. The two primary hypotheses that address attending to pattern structure both incorporate a role for accents of various kinds. Predictions from the pattern-based expectancy and the pattern congruency hypotheses have been summarized in Figures 6.2 and 6.3 (Panels A and B). Also shown in these figures are the results of Experiment 4 WMs at length 10 and length 13 (Panel C). Essentially, the results of Experiment 4 clearly support the predictions from the pattern congruency hypothesis.
In this experiment the intensity accent patterns are relatively incoherent because they are temporally irregular. The pattern-based expectancy hypothesis allows for the possibility that such accents will interfere with attending to the higher-order pattern and force attending to the lower-order structure. Thus, it assumes that the occurrence of random irregularly timed intensity accents may yield sequences that seem less pattern-like. Alternatively, the pattern congruency hypothesis offers different predictions. It assumes that the irregular accent timing of intensity accents will allow listeners to completely ignore the irrelevant intensity variations, as instructed. Under this assumption, the pattern congruency hypothesis correctly predicts that listeners will focus on the higher-order frequency pattern, yielding reversed WMs at period boundaries.

The results of Experiment 4 suggest that the addition of temporally random intensity accents to these periodic frequency patterns had little effect on pitch judgments. The observed WMs rule out the pattern-based expectancy hypothesis. Instead, error shifts at period boundaries are consistent with the pattern congruency hypothesis, which assumes that the irrelevant dimension can be ignored when it forms an incoherent pattern. Essentially, the intensity accents that were employed in this experiment had no impact on error shifts.

Summary

The main goal of Experiment 4 was to investigate whether irregularly timed intensity accent patterns, within a periodic frequency pattern, influence pitch judgments of a subsequent probe tone. The results revealed that the intensity accents (as employed in this experiment) did not influence error shifts. WMs reflected continuation of the
higher-order frequency pattern regardless of intensity accents. Although accuracy was affected by intensity level, this was a result of decreased accuracy when the final induction sequence tone was an intensity accent versus when it was unaccented.

The results of Experiment 4 rule out the pattern-based expectancy hypothesis. The pattern congruency hypothesis, however, did successfully account for the observed error shifts in this experiment. This approach predicted that incoherent intensity structure would allow listeners to ignore the irrelevant intensity variations, as instructed.
Table 6.1. The frequency patterns (arrows) and final intensity accents (circles) in Experiment 4 induction sequences. The location of the final intensity accent is always fixed as shown, leaving two accent locations to randomly vary for IA patterns and one location to vary for IB patterns.
Table 6.2. WMs for each frequency pattern, as a function of intensity pattern and sequence length, in Experiment 4. PC scores are inside parentheses. “*” indicates locations of intensity accents.
Table 6.3. WM for the significant frequency pattern and sequence length interaction in Experiment 4.

<table>
<thead>
<tr>
<th></th>
<th>Frequency</th>
<th>10</th>
<th>11</th>
<th>12</th>
<th>13</th>
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<tr>
<td>$F_A$</td>
<td></td>
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<tr>
<td>$F_B$</td>
<td></td>
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<td>+5.82</td>
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<tr>
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<td>11</td>
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<td>Low</td>
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<td>-2.66</td>
<td>+1.62</td>
<td></td>
</tr>
<tr>
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<td>+2.85</td>
<td>+4.67</td>
<td>-5.79</td>
<td></td>
</tr>
</tbody>
</table>

Table 6.4. WM for the significant sequence length and frequency range interaction in Experiment 4.
Figure 6.1. Example of a 13 tone induction sequence, followed by a probe tone (hatched circle), from Experiment 4. Grey circles represent intensity accents whose serial position randomly varies from trial to trial, and black circles represent serial positions that are always intensity accents. Panel A: an $F_{AIA}$ pattern and Panel B: an $F_{AIB}$ pattern.
Figure 6.2. Error shift predictions from two hypotheses for the length 10 sequences of Experiment 4 (Panel A and B). Panel C displays the observed data.
Figure 6.3. Error shift predictions from three hypotheses for the length 13 sequences of Experiment 4 (Panel A and B). Panel C displays the observed data.
Figure 6.4. WMs as a function of length, for sequences with a congruent final intensity accent (Panel A) and an incongruent final intensity accent (Panel B) in Experiment 4.
CHAPTER 7
GENERAL DISCUSSION

Most auditory events listeners encounter on a daily basis contain frequency and intensity changes that occur over time. For example, in music, the frequency values of successive tones vary to create a melody, namely a temporally ordered arrangement of pitches. In addition, the intensity values of successive tones in melodies can also vary to create crescendos and decrescendos or they may form discrete accent patterns. However, little research has been undertaken to investigate the joint effects of dynamic frequency and intensity changes on the perception of pitches that comprise a sound pattern.

Research on auditory representational momentum (RM) has shown that when listeners hear a sequence of tones that increase or decrease in frequency (holding intensity constant), their judgments of a final probe tone’s pitch are shifted in the direction implied by the context sequence (Freyd, Kelly, & DeKay, 1990; Hubbard, 1995a; Kelly & Freyd, 1987). However, there is also evidence that perceived pitch is influenced by intensity. Using isolated tones as stimuli, research on pitch perception indicates that intensity variations can influence pitch perception (Grau & Kemler-Nelson, 1988; McBeath & Neuhoff, 2002; Melara & Marks, 1990b; Stevens, 1934). But, the effects of intensity on pitch perception have not been explored using longer tone sequences that are typically employed in the auditory RM paradigm. The goal of this dissertation is to investigate whether dynamic intensity changes within a context
sequence will also influence pitch perception of a final probe tone, even though intensity manipulation are irrelevant in this task (Yantis & Egeth, 1999). Accordingly, a series of pitch judgment tasks were used to investigate how various frequency and intensity patterns within dynamic auditory sequences may influence performance in a pitch perception task where intensity variations, but not frequency variations, are technically irrelevant.

The results of the current experiments indicate that irrelevant intensity variations within a frequency pattern do affect pitch judgments of a subsequent probe tone. These results have implications for a number of hypotheses, developed from research literature, that are concerned with perception of pitch. These include the environmental invariants hypothesis, the pattern-based expectancy hypothesis, the isolated tone pairs hypothesis, and the dimensional interaction hypothesis. In addition, the findings from these experiments provide the foundation for a new theoretical orientation, the pattern congruency hypothesis, which will be discussed later in detail.

First consider hypotheses developed from the RM literature. Hubbard’s (1995b) environmental invariants hypothesis proposes that the mental representation of an object that implies motion has properties similar to a physical object with momentum. In translating this hypothesis to the auditory domain, pitch change is associated with velocity and intensity is analogous to mass. This approach predicts that given a sequence of tones that imply increasing or decreasing frequency, pitch judgment errors should be shifted in the direction associated with continuation of the immediately preceding monotonic pitch trajectory. In addition, when the intensity of tones in a sequence increase (or are constantly loud) momentum should increase, and in turn increase the absolute
magnitude of error shifts. Conversely, when the intensity of tones in a sequence decrease (or are constantly soft) momentum should decrease, and in turn decrease the absolute magnitude of error shifts. Alternatively, Johnston and Jones’ (in press) pattern-based expectancy hypothesis suggests that pitch judgment error shifts reflect expectations regarding upcoming events that are based on the event structure of the experienced pattern, not an internalization of invariant physical principles. This approach considers simple patterns, e.g., monotonic trajectories, and more complex patterns, e.g., periodic patterns. Thus, this view allows for pattern structure that can transpire over different, yet related, time levels. For example given a complex frequency pattern, the lower-order structure refers to time spans associated with the linear change in frequency between adjacent tones, whereas the higher-order structure refers to time spans associated with non-adjacent period boundaries that mark regularly recurring changes in the frequency trajectory. This hypothesis applies generally to patterning along any dimension of change, and it assumes that temporal coherence between dimensions contributes to the perception of a pattern. However, it does not explicitly address how patterns within the frequency and intensity dimensions combine or interact to affect performance in this pitch judgment task. This and the environmental invariants hypothesis make no predictions regarding how these frequency and intensity patterns will affect accuracy.

Other hypotheses do address the possibility of interactions of frequency with intensity in a pitch perception task. These derive from research which uses isolated tones as stimuli, instead of tone sequences. The isolated tone pairs hypothesis posits that listeners should be more accurate at judging the pitch of tones with low, versus high, intensities. In addition, with greater intensities pitch judgment errors may be shifted
toward lower probes. Another hypothesis, the *dimensional interaction hypothesis*, derives from research on congruency between frequency and intensity using multidimensional stimuli and dynamic auditory glides. It predicts that listeners’ pitch judgments should be more accurate (high PC) when the frequency and intensity values of probe tones are positively correlated, i.e., congruent, versus negatively correlated, i.e., incongruent. The present research evaluated a version of this hypothesis that adapted this rationale to tone sequences. If time is included as a third dimension within which frequency and intensity can be positively or negatively correlated, then congruency effects generalize to the longer auditory sequences that are employed in the current research. However, under this approach, descriptions of pattern structure are limited to monotonic changes along dimension over time; thus, error shifts may reflect continuation of the linear frequency trajectory and these shifts may be greater when pitch and loudness changes are positively versus negatively correlated.

Four experiments were designed to test predictions from these hypotheses. Induction sequences in these experiments were tone sequences that implied either monotonic or periodic motion over time in pitch space. In addition, intensity was manipulated such that intensity patterns were congruent or incongruent with these frequency patterns, either through graduated level changes or through step changes, leading to intensity accents. The most important finding from these studies was that intensity changes within induction sequences did influence pitch judgments. Specifically, congruency between the frequency and intensity changes differentially effected error shifts for certain monotonic and periodic frequency patterns. The nature of these findings, however, indicated that none of the four original hypotheses entirely explained
performance. As a result a fifth and final hypothesis was proposed, the pattern congruency hypothesis. The following two sections, discuss in more detail the evidence in favor of the pattern congruence hypothesis and, more generally, the merits and demerits of this hypothesis.

**Monotonic frequency patterns**

The simplest case for comparing predictions of different perspectives occurs when listeners are exposed to simple four tone sequences that contain monotonic changes in frequency and intensity. This case was examined in Experiment 1B. Thus, listeners heard four-tone sequences that comprise linearly increasing or decreasing frequency patterns and increasing, decreasing, constant soft or constant loud intensity patterns, followed by a to-be-judged probe tone.

These simple patterns offer a basis for testing all four of the original hypotheses. However, the data collected with these sequences paved the way for development of the fifth hypothesis, based on pattern congruency. Of the four original hypotheses, the environmental invariants hypothesis predicts that errors with these patterns will be shifted in the direction implied by the preceding linear frequency trajectory (due to pitch velocity); moreover, error shifts should be larger when intensity is increasing or constantly loud (analogous to increased mass) than when intensity is decreasing or constantly soft. The pattern-based expectancy hypothesis predicts that error shifts will reflect continuation of the experienced pattern. However, it does not predict an influence of linear intensity changes on errors. The isolated tone pairs hypothesis predicts that with louder tones, errors should be shifted toward low frequency probes and that accuracy
should decrease. Finally, the dimensional interaction hypothesis predicts that pitch judgments will be more accurate with congruent sequences compared to incongruent sequences. In addition, it predicts that when frequency and intensity changes are congruent, large error shifts will reflect continuation of this linear trajectory; however, when changes in these dimensions are incongruent, small error shifts will be observed.

The results observed with the monotonic sequences in Experiment 1, indicate that intensity changes do influence pitch judgments. With these patterns, a significant congruency effect was observed: error shifts (WMs) were greater when frequency and intensity were congruent, i.e., positively correlated, than when they were incongruent, i.e., negatively correlated. Thus, with congruent sequences, listeners’ errors were shifted toward probe tone frequencies that were consistent with continuation of the implied (linear) frequency trajectory. Moreover, error shifts with congruent patterns were similar in nature to those found for similar patterns, in which intensity was not varied (i.e., Experiment 1A). This was not true when frequency and intensity were incongruent. By contrast, with incongruent changes, listeners’ error shifts were generally small and the direction of errors actually reversed for increasing frequency sequences. Although, pitch judgment errors associated with incongruent sequences showed less bias (small WMs), overall accuracy (PC) was similar with both congruent and incongruent sequences. This indicates that with incongruent sequences listeners were more likely to respond ‘same’ to both higher and lower probes, instead of being biased to respond ‘same’ to probes that were shifted in one direction.

These results rule out two of the four original hypotheses proposed for this research. The environmental invariants hypothesis and the isolated tone pairs hypothesis
both fail to account for major aspects of the results. Some support is found for the remaining two hypotheses, pattern-based expectancy and dimensional interaction. However, the pattern-based expectancy hypothesis has no explicit predictions regarding how intensity changes influence pitch perception and thus it cannot explain why the magnitude of the error shifts are greatly reduced for incongruent patterns. The best account is provided by the dimensional interaction hypothesis. As developed here, this approach assumes that listeners are biased to expect frequency and intensity to be positively correlated. Consequently, it predicts that when frequency and intensity changes are positively correlated over time, i.e., as a tone sequence unfolds, listeners will be biased toward probe tone frequencies that preserve this positive correlation. However, when frequency and intensity changes are negatively correlated over time, this bias will disappear, yielding small error shifts. This is exactly what was observed. Errors were shifted in the direction consistent with the experienced frequency pattern with congruent sequences and error shifts were greatly reduced, or reversed, with incongruent sequences.

Clearly the dimensional interaction hypothesis provides a good account of the findings observed in Experiment 1, where stimuli involved only monotonic auditory patterns. However, it is not necessarily the ideal explanation for all of the effects observed in the present research. This is because the dimensional interaction hypothesis was adapted to apply to sequences by assuming that frequency and intensity changes may be correlated across individual tone values that are ordered uniformly along a third dimension, time. As a result, this mapping leads the dimensional interaction hypothesis to focus on the linear, namely lower-order pattern structure, formed by correlated frequency and intensity changes that occur over a series of adjacent tones. Although this adaptation
lends greater power and generality to the original approach to dimensional interactions, it continues to remain limited in the degree to which it can be readily applied to patterns other than linear, i.e., monotonic, correlated pitch and loudness changes.

A new hypothesis was developed in this research that addresses both complex pattern structure and dimensional congruency: the pattern congruency hypothesis. This hypothesis combines successful aspects of both the pattern-based expectancy and the dimensional interaction hypotheses. It assumes that both the frequency changes and the intensity changes employed here are patterns. In agreement with the pattern-based expectancy hypothesis, this view also allows for pattern structure that can transpire over different, yet related, time levels, to create simple or complex patterns. At lower levels, markers of pattern structure can involve graduated changes along various (correlated) dimensions; at higher levels, markers of pattern structure are more pronounced changes, e.g., intensity accents or frequency peaks and troughs, that may also be correlated across various dimensions. Therefore, pattern structure is associated with relationships between adjacent and nonadjacent tones within a sequence. Thus, in contrast to the dimensional interaction hypothesis, the pattern congruency hypothesis is not limited to frequency and intensity correlations within the lower-order serial structure. In addition, the relationship between the frequency and intensity patterns can be congruent, with frequency and intensity changing similarly, or incongruent, with frequency and intensity changing in different directions.

A second feature of the pattern congruency hypothesis concerns task-relevance. In all of the experiments in this study, intensity variations are technically irrelevant to the task of pitch perception. However, this hypothesis assumes that when an intensity pattern
is congruent, i.e., correlated, with a frequency pattern, it is difficult for listeners to ignore intensity variations. In this case, the frequency pattern, which is the relevant dimension, is reinforced by the positively correlated changes along an irrelevant dimension.

Conversely, when an intensity pattern is incongruent with a frequency pattern, the irrelevant intensity pattern may be distracting due to the negatively correlated changes along an irrelevant dimension. In the latter case, the frequency pattern may not be as compelling and any bias associated with the frequency pattern will be reduced. In other words, intensity changes that are both irrelevant and incongruent may interfere with a listener’s ability to attend to the frequency pattern.

The pattern congruency hypothesis generates the same predictions as the dimensional interaction hypothesis when it is applied to simple monotonic sequences as in Experiment 1. However, the two hypotheses predict very different outcomes with more complex patterns. This is because the pattern congruency hypothesis does not rely solely on lower-order correlations between frequency and intensity changes to explain error shifts. Instead it assumes that induction sequences are composed of frequency and intensity patterns that can be simple or complex; and expectations regarding upcoming tones are influenced by pattern congruency.

Periodic frequency patterns

The remaining experiments in this research employ more complex auditory patterns. These studies were inspired by a recent auditory RM experiment by Johnston and Jones (in press). In their experiment, induction sequences implied periodic increasing and decreasing motion in frequency space. Specifically, all sequences exhibited pattern
structure that transpired over two different (related) time levels. The lower level related successive tones within monotonic four tone sequences and the higher level related constant period boundaries (frequency peaks and troughs) that marked successive increasing or decreasing frequency trajectories within sequences. When the probe tone occurred at a period boundary, listeners errors reflected anticipation of the change in frequency direction associated with the higher-order periodic pattern and not extrapolation of the immediately preceding, lower-order, frequency trajectory. The findings of Johnston and Jones are extended in the present research. Experiments 2, 3, and 4 examine how pitch judgments are influenced by intensity changes within these periodic frequency patterns. To this end, the same periodic increasing and decreasing frequency patterns are used in these experiments. However, each experiment employs a different type of intensity pattern. In Experiment 2, intensity manipulations imply periodic, increasing and decreasing loudness patterns that are congruent or incongruent with frequency patterns. In Experiment 3, intensity manipulations consist of intensity accent patterns that are temporally regular, i.e., coherent, and which may be either congruent or incongruent with the periodic frequency pattern. In these sequences, congruent accents occur at frequency peaks and incongruent accents occur at frequency troughs. Finally in Experiment 4, intensity manipulations consist of temporally irregular intensity accents that occur randomly throughout these sequences. This manipulation serves to create intensity accents patterns that are temporally unpredictable, i.e., incoherent, and conflict with the predictable frequency pattern.

These experiments evaluate three hypotheses: the pattern-based expectancy hypothesis, the dimensional interaction hypothesis, and the pattern congruency
hypothesis. Each hypothesis offers specific predictions regarding pitch judgment errors in these experiments. Consider first the simplest version of the pattern-based expectancy approach as outlined in the introduction. For both Experiments 2 (periodic loudness patterns) and 3 (regular intensity accents) a simple pattern-based expectancy hypothesis predicts that error shifts will reflect continuation of the experienced higher-order frequency pattern. The sequences used in these experiments are considered temporally coherent because the regular time intervals between frequency period boundaries match the regular time intervals that occur between intensity peaks and troughs in Experiment 2 and the regular time intervals that occur between intensity accents in Experiment 3. As a result, these sequences should be perceived as coherent patterns. However, this approach does not specifically address how intensity patterns will influence pitch judgments in this task. By contrast, in Experiment 4, sequences are temporally incoherent because the regular time intervals between frequency period boundaries do not match the time intervals that obtain between the temporally irregular intensity accents. In this case, the pattern-based expectancy hypothesis predicts that temporally irregular intensity accents may disrupt attending. As a result, the periodic frequency changes may seem less pattern-like. Thus, this approach predicts that error shifts will reflect continuation of the lower-order frequency trajectory immediately preceding the probe.

Second, the dimensional interaction hypothesis focuses solely on correlations within lower-order structure. Consequently, although this hypothesis performed well with simple monotonic patterns, its limitations become evident when stimuli consist of more complex periodic frequency patterns. This hypothesis makes the same predictions for Experiments 2 (periodic loudness patterns), 3 (regular intensity accents), and 4 (irregular
intensity accents). It assumes that error shifts will reflect continuation of the lower-order (linear) structure and that the magnitude of this shift will be greater when frequency and intensity changes are positively correlated (congruent) than when changes in these dimensions are incongruent.

Finally, the pattern congruency hypothesis provides the most promising approach. For both Experiments 2 (periodic loudness patterns) and 3 (regular intensity accents) this hypothesis predicts that error shifts will reflect continuation of the experienced higher-order frequency pattern; and that the magnitude of the error shifts will be greater when the irrelevant intensity changes are congruent versus incongruent with the frequency pattern. In Experiment 4, however, sequences contain incoherent intensity patterns because the intensity accents are temporally unpredictable within the context of the temporally regular frequency pattern. The pattern congruency hypothesis predicts that with these sequences, the incoherence of the intensity pattern will enable listeners to ignore irrelevant intensity variations. As a result, listeners will focus on the higher-order frequency pattern; and the direction of WM s at the period boundaries will reflect continuation of the periodic frequency pattern.

Taken together, results from these experiments indicate that intensity changes do influence pitch judgments. Considering the structure of these periodic frequency patterns, analyses focus on error shifts that occur for probe tones that follow a period boundary, i.e., the onset of a frequency direction change. In Experiments 2, 3, and 4, the majority of error shifts at these locations were consistent with continuation of the higher-order periodic frequency pattern and not of the lower-order linear frequency trajectory. In addition, for certain sequences in Experiment 2 and 3 a congruency effect was observed:
error shifts (WMs) were differentially affected by whether frequency changes and intensity changes in the induction sequences were congruent or incongruent. This is especially evident in two experiments. First, in Experiment 2B, where intensity patterns covaried continuously with frequency patterns, the $F_A$ patterns open with a falling pitch pattern and end with a rising one; at the period boundary of location 10, listeners' error shifts reflect anticipation of this final rising segment and the magnitude of the shift is larger for congruent versus incongruent patterns. Second, in Experiment 3, where sequences contained regularly timed intensity accents, for both $F_A$ patterns and $F_B$ patterns, listeners' error shifts at the final location (length 13) reflect anticipation of a frequency direction change and the magnitude of the shift is larger for congruent versus incongruent patterns. Nevertheless, for other sequences in Experiments 2 and 3, error shifts at period boundaries were generally small. Although small or reversed error shifts are consistent with the higher-order frequency pattern influencing pitch judgments (Verfaillie & d’Ydewalle, 1991), no congruency effects were evident at these locations. Finally, when sequences contained irregularly timed intensity accents (Experiment 4), results suggest that intensity had no effect on pitch judgment error shifts.

The results from Experiments 2, 3, and 4 clearly rule out the dimensional interaction hypothesis proposed in this research. This approach can only predict congruency effects that are specific to the lower-order structure of the induction sequence. Thus, the observed error shifts, which are consistent with the higher-order pattern structure (in Experiments 2 – 4), directly conflict with predictions from this approach. Instead greater support is found for the pattern-based expectancy hypothesis and particularly for the pattern congruency hypothesis. Both of these approaches
correctly predict that errors will be shifted in the direction consistent with the experienced higher-order frequency pattern, in Experiments 2 and 3. However, only the pattern congruency hypothesis correctly predicted the congruency effect that was observed with certain sequences (Experiment 2B: length 10 F_A patterns; Experiment 3: length 13 F_A and F_B patterns). In addition, only the pattern congruency hypothesis correctly predicted that listeners would be able to ignore the irrelevant and temporally irregular intensity accents in Experiment 4.

Limitations of the Pattern Congruency Hypothesis

The proposed pattern congruency hypothesis has a great deal of success in accounting for the results of the experiments in this research. It correctly described all of the observed error shifts for the monotonic patterns used in Experiment 1 and the temporally incoherent patterns used in Experiment 4. However, this hypothesis encountered some difficulty with periodic frequency patterns that contained coherent intensity patterns (Experiments 2 and 3). This hypothesis predicted that error shifts with these sequences would reflect continuation of the experienced higher-order frequency pattern and that the magnitude of the error shifts would be relatively greater with congruent compared to incongruent patterns. This prediction only obtained in Experiment 2B with length 10 F_A patterns and in Experiment 3 with length 13 F_A and F_B patterns. Essentially, all other patterns (Experiment 2B: length 10 F_B and length 13 F_A and F_B; Experiment 3: length 10 F_A and F_B) yielded WMs that did not differ as a function of congruency.
Conclusions

The problem addressed in this dissertation concerns ways in which pitch perception is influenced by a context of dynamically changing frequency and intensity patterns. Research on auditory RM has shown that a linear or periodic frequency pattern influences pitch judgments of a subsequent probe tone (Freyd, et al., 1990; Hubbard, 1995a; Kelly & Freyd, 1987). In turn, research from many domains has shown that pitch perception of isolated tones can be influenced by intensity variations (Grau & Kemler-Nelson, 1988; McBeath & Neuhoff, 2002; Melara & Marks, 1990b; Stevens, 1934).

Given these findings it seems logical to assume that linear and/or periodic frequency and intensity patterns may also influence pitch judgments of a subsequent probe tone. Results from the current experiments indicate that this is the case. Most interestingly, it is not simply the presence of intensity variations that influences pitch judgments. In addition, it is the relationship between the frequency and intensity patterns within an induction sequence, be it congruent or incongruent, that influences pitch judgments. Congruency effects found in this study support and extend the findings of research with dynamic stimuli (Neuhoff, Wayand, & Kramer, 2002; Scharine, 2003) and research on the perception of multidimensional stimuli (Melara & Marks, 1990b). Essentially, using a variety of tasks and stimuli it has been found that the perception of pitch is influenced by congruency between frequency and intensity.

In extending previous research, the present study offers a new approach to dimensional congruency that applies to auditory patterns. In particular the proposed pattern congruency hypothesis, offers a new way to apply concepts of multidimensional congruency to more realistic auditory events such as speech and music. Considering the
results of the experiments conducted here, this hypothesis provides the most reasonable explanation of the observed data. It assumes that when listeners hear a coherent auditory pattern they form expectancies regarding attributes of future events. These expectancies are based on pattern relationships that develop between adjacent and/or nonadjacent events in the sequence along multiple dimensions, including the dimensions of frequency and intensity. In addition, this hypothesis assumes that the way in which frequency and intensity values are structured within a sequence influences perception. Specifically, when frequency and intensity change similarly, e.g., both increasing, this forms a congruent pattern. Conversely, when frequency and intensity change in opposite directions, e.g., frequency increases as intensity decreases, this forms an incongruent pattern. These congruent and incongruent patterns are still coherent however, because the changes within these dimensions are regularly timed.

Jones (1976; 2001; Jones & Boltz, 1989) has argued that dynamic attending to pattern structure operates over multiple (related) time spans. In this view, attending itself is rhythmically sensitive; attending periodicities of different frequencies can entrain, namely “lock into”, corresponding time levels in a temporal sequence. Considering the periodic frequency and intensity patterns employed in Experiments 2 and 3, it is likely that certain attending periodicities synchronize, i.e., entrain, to the higher-order periodic pattern. If attending energy is targeted to the relevant frequency dimension and is regularly timed, then congruent intensity patterns may reinforce the relevant dimension whereas incongruent intensity patterns could weaken attending to the relevant dimension. This would explain the congruency effects observed in Experiment 2 and 3. In addition, if attending periodicities entrain to the relevant higher-order periodic frequency pattern in
Experiment 4, then less energy may be targeted to the irregularly timed intensity accents, which never occur at a period boundary. This can explain why listeners seemed to be able to easily ignore the irrelevant and incoherent intensity accents.

In summary, according to the pattern congruency approach, when listeners are instructed to attend to pitch and ignore intensity, congruent patterns will reinforce attending to the relevant frequency pattern and incongruent patterns will not. Based on these assumptions, when a listener hears a sequence of tones that imply a simple or complex pattern in pitch space, their pitch judgment errors should reflect a bias towards continuation of the experienced pattern when frequency and intensity patterns are congruent. Conversely, this bias decreases when the co-occurring intensity pattern is incongruent with the frequency pattern. Finally, when the intensity pattern is temporally irregular, it becomes much easier for listeners to ignore this irrelevant dimension, as instructed.

The pattern congruency hypothesis can not only address periodic pattern structure but also monotonic structure. It is most successful in explaining the results of Experiment 1, which used linearly increasing or decreasing frequency and intensity patterns. This hypothesis accounts for all aspects of the observed data in this experiment. It is also successful with explaining the congruency effects that were observed at period boundaries for select sequences in Experiment 2 and 3. However, for the majority of sequences error shifts were small, consistent with the higher-order frequency pattern, and showed no influence of congruency. One possible explanation for the reduced impact of intensity variations on error shifts in Experiments 2 and 3, is that with longer sequences the intensity changes may not have been as salient as they were in the shorter patterns of
Experiment 1. In the initial rating experiment, where listeners judged whether frequency and intensity changes were equivalent, trials contained short four-tone sequences. Perhaps with longer periodic frequency patterns, the frequency and intensity changes were no longer perceptually equivalent. It is possible that with longer sequences it may be easier for listeners to ignore intensity changes, as instructed, and simply focus on the frequency pattern. Future research with rating experiments that contain longer sequences and/or using larger intensity changes in the periodic frequency patterns will address this issue.

Summary

The main goal of this dissertation was to determine whether dynamic intensity changes, like dynamic frequency changes, also contribute to pattern-based expectations in listeners. In a series of four experiments, listeners heard context sequences of tones that changed dynamically in frequency and intensity, and judged whether the pitch of a final probe tone was the same as or different from the immediately preceding tone. Experiment 1 sequences comprised simple monotonically changing frequency and intensity patterns. In Experiment 2, listeners heard longer sequences that implied periodically changing frequency and intensity patterns. And using the same frequency patterns from Experiment 2, Experiment 3 incorporated regularly recurring intensity accents and sequences in Experiment 4 included randomly occurring intensity accents. Results are most consistent with the proposed pattern congruency hypothesis.
LIST OF REFERENCES


This experiment is essentially a replication of Experiment 2B with intensity pattern serving as a between subjects variable instead of as a within subjects variable. The goal of this experiment was to ensure that any effects of intensity were due to the intensity pattern itself and not due to varying intensity pattern from trial-to-trial. The results indicate that experimental design did not change performance as compared to Experiment 1B.

Method

Subjects. Eighty-four undergraduate students with normal hearing and fewer than ten years of formal musical training (mean = 1.8 years) participated in this experiment in exchange for credit in the introductory psychology course at The Ohio State University. The data from two participants were discarded, as they responded to fewer than 80% of trials.

Apparatus. All equipment used was identical to the rating experiment.

Stimuli. All patterns were from Experiment 2B.

Design. Frequency pattern, $F_A$ or $F_R$, and intensity pattern ($I_A$ and $I_R$) served as between subjects variables. Therefore subjects were randomly assigned to one of four
groups corresponding to each type of frequency/intensity pattern, $F_{AI_A}$ ($n = 27$), $F_{BI_B}$ ($n = 19$), $F_{AI_B}$ ($n = 17$), and $F_{BI_A}$ ($n = 19$). Within subjects variables included length of the induction sequence (10, 11, 12, and 13 tones), frequency range (low and high), and frequency shift of the probe tone (-70 c, -35 c, 0 c, +35 c, and +70 c). This resulted in a 2 x 2 x (4 x 2 x 5) mixed factorial design, and a total of 160 unique sequences. In each group, listeners heard the 40 patterns associated with a particular frequency/intensity pattern three times.

*Procedure.* Instructions were identical to Experiment 2B and the number of test blocks and trials were identical to Experiment 2A.

*Dependent Measures.* Same as Experiment 2.

*Results and Discussion*

Table A.1 presents the average WM and PC scores for each frequency pattern as a function of intensity pattern (congruent and incongruent) and sequence length, collapsed over the frequency range variable.

A mixed ANOVA was conducted using WMs, with frequency pattern and congruency as between subjects variables and sequence length and frequency range as within subjects variables. This revealed three significant effects. There was a main effect of frequency pattern [$F (1, 78) = 4.79$, $MSE = 374.56$, $p = .03$], a main effect of sequence length [$F (3, 234) = 6.22$, $MSE = 175.59$, $p < .01$], both qualified by a significant interaction of frequency pattern and sequence length [$F (3, 234) = 7.25$, $MSE = 175.59$, $p < .01$]. The observed WMs for this interaction are presented in Table A.2. Trend analyses revealed a significant linear trend over sequence length with the $F_B$ pattern [$F_B: F (1, 78)$

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= 16.17, \( MSe = 207.72, p < .001; F_A: p = .20 \), along with a significant difference between the \( F_A \) and \( F_B \) patterns \([F (1, 78) = 14.46, MSe = 207.72, p < .001]\). Similar to the findings of Experiment 2, these results suggest that the higher-order frequency pattern, not the lower-order linear trajectory, influenced pitch judgments at period boundaries. WMs at both length 10 and 13 period boundaries are reversed. These results can be interpreted as consistent with the pattern-based expectancy and pattern congruency hypotheses, as both predict that error shifts at period boundaries should reflect continuation of the higher-order frequency pattern.

No effects of congruency were observed in this experiment. That is, the three way interaction of frequency pattern, congruency, and sequence length was not significant, \( p = .46 \). Thus, congruency of frequency and intensity did not differentially increase (or decrease) the magnitude of errors at certain locations in the pattern. The relevant WMs are displayed in Table A.1. Planned comparisons conducted to test for an interaction of frequency pattern and congruency at each sequence length, confirmed that no significant differences were present. And for each frequency pattern, planned comparisons conducted to investigate whether the magnitude of WMs differed for congruent versus incongruent patterns at each sequence length also found no significant differences.

Finally, differences in WMs based on frequency pattern and congruency at the period boundaries can be examined. The observed data are graphically displayed for length 10 in Panel D of Figure A.1 and for length 13 in Panel D of Figure A.2. In addition, predictions from the pattern-based expectancy hypothesis (Panel A), predictions from the pattern congruency hypothesis (Panel B), and the observed data from Experiment 2B (Panel C) are also displayed. In examining the observed data, the WMs at
both length 10 and 13 indicate that listeners are focused on the higher-order frequency pattern and that WMs are not modulated by congruency. These results most closely follow predictions from the pattern-based expectancy hypothesis. It seems that when listeners only receive one type of irrelevant intensity pattern, any effects of pattern congruency are diminished.
Table A.1. WMs for each frequency pattern, as a function of intensity pattern, for the follow-up of Experiment 2B (intensity pattern is a between subjects variable). PC scores are inside parentheses.
Table A.2. WMs for the significant frequency pattern and sequence length interaction in the follow-up of Experiment 2B (intensity pattern is a between subjects variable).
Figure A.1. Error shift predictions for the length 10 sequences from the pattern-based expectancy (Panel A) and the pattern congruency (Panel B) hypotheses. Panel C displays observed data from Experiment 2B. Panel D displays observed data from the follow-up of Experiment 2B (intensity pattern is a between subjects variable).
Figure A.2. Error shift predictions for the length 13 sequences from the pattern-based expectancy (Panel A) and the pattern congruency (Panel B) hypotheses. Panel C displays observed data from Experiment 2B. Panel D displays observed data from the follow-up of Experiment 2B (intensity pattern is a between subjects variable).