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Dynamic Frequency Change Influences Loudness Perception: A Central, Analytic Process

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Three experiments showed that dynamic frequency change influenced loudness. Listeners heard tones that had concurrent frequency and intensity change and tracked loudness while ignoring pitch. Dynamic frequency change significantly influenced loudness. A control experiment showed that the effect depended on dynamic change and was opposite that predicted by static equal loudness contours. In a 3rd experiment, listeners heard white noise intensity change in one ear and harmonic frequency change in the other and tracked the loudness of the noise while ignoring the harmonic tone. Findings suggest that the dynamic interaction of pitch and loudness occurs centrally in the auditory system; is an analytic process; has evolved to take advantage of naturally occurring covariation of frequency and intensity; and reflects a shortcoming of traditional static models of loudness perception in a dynamic natural setting.

The notion that changes in auditory pitch are perceptually distinct from changes in loudness is intuitively appealing. However, in some cases, the distinction between such changes may not be an easy one to make. For example, the pitch of an approaching train can rise while the observed frequency actually falls (Neuhoff & McBeath, 1996). The rising dynamic intensity change that occurs as the train draws closer can influence pitch and make it difficult to accurately track the falling frequency. Thus, under dynamic conditions, pitch and loudness interact.

In the present study, we examined this interaction in greater detail. Specifically, we explored whether dynamic frequency change would influence loudness in the same way that dynamic intensity change can influence pitch. We also examined the nature of this interaction. We used a dichotic listening task to explore whether the dynamic interaction of pitch and loudness occurs in the central or peripheral auditory system and whether the interaction occurs because the two stimulus dimensions are processed holistically (Kemler-Nelson, 1993) or whether it is because of the context produced by the unattended dimension (Melara, Marks, & Potts, 1993a). In addition, we propose that the interaction between dynamic pitch and loudness occurs because of an internalization or bias that reflects a correlation between naturally occurring changes in frequency and changes in intensity.

Garner (1974) proposed a set of converging operations (speeded sorting, restricted classification, and dissimilarity scaling) that is used to determine the interactive nature of a set of perceptual dimensions. Participants are typically presented with stimuli that vary along two dimensions, such as pitch and loudness, and are instructed to attend to one dimension and ignore the other. If discrete variation of the unattended dimension influences performance on the attended dimension, the two dimensions are said to interact. Although the set of converging operations uses only discrete static stimuli, and the specifics of the dimensional interaction are of some dispute, pitch and loudness have nonetheless been shown to interact (Grau & Kemler-Nelson, 1988; Melara & Marks, 1990b, 1990c).

However, in a natural listening environment, people rarely encounter sounds that do not dynamically change in frequency, intensity, or both. It is curious, then, that almost all previous work on the dimensional interaction between pitch and loudness has used discrete static sounds. Indeed, much of the traditional knowledge of psychophysics is based on experiments in which perceivers were presented with static unchanging stimuli. However, there is a growing body of work that demonstrates that under many circumstances, the perception of dynamic ecologically valid stimuli is not well predicted by the results of static stimuli experiments. Differences between static and dynamic perception have recently been investigated in vision (Kleiss, 1995; Muise, LeBlanc, Blanchard, & de Warnaffe, 1993; Verstraten et al., 1996), audition (Canévet & Scharf, 1990; Iverson, 1995; Neuhoff & McBeath, 1996; Perrott & Musicant, 1981;

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Spillmann & Kurtenbach, 1992; Spitzer & Semple, 1993), and haptics (Menier, Forget, & Lambert, 1996; Rochat & Wraga, 1997). Together, these findings suggest that using the results of static stimuli experiments to predict dynamic perception is often untenable.

Our recent work shows that dynamic pitch change can be influenced by dynamic intensity change. In some situations, pitch change can be almost entirely due to dynamic intensity change. The pattern of rising intensity produced by an approaching sound source, for example, can lead to the perception of rising pitch even though frequency falls, a phenomenon we have called the "Doppler illusion" (Neuhoff & McBeath, 1996). The effect demonstrates dramatic differences in dynamic versus static pitch perception and is qualitatively different from the well-known and much smaller effect of discrete intensity change on pitch found by Stevens (1935).

Static structural models of pitch such as the mel scale (Stevens, Volkmann, & Newman, 1937), helix models (Shepard, 1982), and equal pitch contours (Stevens, 1935) do not account for the influence of dynamic intensity change on pitch. In fact, the effect of dynamic intensity change on pitch can be exactly the opposite of that proposed by equal pitch contours (Neuhoff & McBeath, 1996). In this research we explored the reciprocal effect of dynamic frequency change on loudness and tested the ability of static equal-loudness contours (Fletcher & Munson, 1933) to predict loudness change given a dynamic change in frequency.

In experiments in which static tones have been used, a reciprocal relationship has been found between pitch and loudness (Grau & Kemler-Nelson, 1988; Marks, 1989; Melara & Marks, 1990a, 1990b; Melara, Marks, & Lesko, 1992; however, see Melara & Marks, 1990c). Variation in frequency from trial to trial influences performance on judgments of loudness, and variation in intensity influences judgments about pitch. However, with dynamic stimuli, to our knowledge, only the influence of intensity change on pitch has been examined. Given the reciprocal relationship of pitch and loudness with static tones, it seems reasonable to hypothesize that dynamic frequency change might influence loudness change.

To test this hypothesis, we presented listeners in Experiment 1 with tones that exhibited concurrent changes in frequency and intensity and asked them to track changes in loudness. We hypothesized that dynamic frequency change would influence judgments of loudness in the same manner that dynamic intensity change influences pitch (Neuhoff & McBeath, 1996). To determine whether dynamic change was a necessary component, we had listeners in Experiment 2 estimate the loudness of static tones that were of the same terminal frequency and intensity as the dynamic tones in Experiment 1. In Experiment 3 we used a dichotic listening task to assess whether the interaction of dynamic pitch and loudness perception is a central or peripheral process and whether the process is principally holistic or analytic.

Experiment 1

Method

Participants. Five male and 11 female introductory psychology students served as participants. All were between the ages of 18 and 23 years. All were volunteers who received class credit for participation and were naive about the hypothesis being tested. None were professional musicians or music majors, and none had any formal music training past high school. (Musicians have been found to have better selective attention to auditory dimensions in dimensional interaction experiments; Pitt, 1994.) All participants reported normal hearing.

Stimuli. Stimuli consisted of either a rising, constant, or falling frequency square wave tone that either rose, fell, or remained constant in intensity (see Figure 1). Square waves were composed of odd harmonics 1–21. Each odd harmonic had an amplitude equal to $1/n$ of the amplitude of the fundamental, where n = harmonic number. Tones initiated with a frequency of 1047 Hz and then either rose to 1109 Hz, fell to 988 Hz, or remained constant. Rising intensity stimuli initiated at 70 dB SPL and rose to 85 dB SPL. Falling intensity stimuli initiated at 85 dB SPL and then fell to 70 dB SPL. Constant-intensity stimuli were 75 dB SPL. Tones had a duration of 6 s, had rise and decay times of 10 ms, and were presented in random order with an interstimulus interval of 3 s.

Apparatus. Stimulus tones were generated by a Korg DSM 1 tone generator at a sampling rate of 44.1 kHz. The intensity, frequency, and presentation of the tones were controlled by an IBM-compatible PC. Responses were made on the vertically mounted controller wheel of a Casio CZ-1 synthesizer and recorded by the computer. The response wheel had a notched zero point and was spring loaded so that it returned to this zero point after each trial. The maximum and minimum values on the wheel

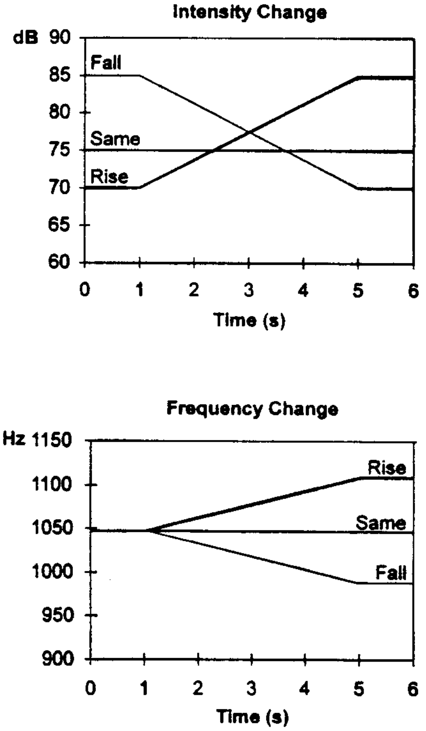

Figure 1. Stimuli used in Experiment 1.

were 127 and −127, respectively, and the wheel had a total travel of approximately 110°. The stimuli were presented through Realistic LV-20 headphones.

Design and procedure. Participants were tested individually in a sound-attenuating booth. A 3 × 3 design was used with the main factors of frequency (rising, constant, and falling) and intensity (rising, constant, and falling). Participants were presented with 4 trials of each type of stimulus, resulting in a total of 36 trials. Each participant's responses were averaged to obtain a single score in each of the nine stimulus conditions.

Participants were told that they would hear a series of tones that could change in pitch as well as loudness. It was then explained that changes in pitch were changes in the highness or lowness of a tone and that changes in loudness meant that the tone could get louder or quieter. Any additional questions about the difference between pitch and loudness were answered. Participants were then instructed to listen carefully to the tones for any changes in loudness and to ignore any changes in pitch. Participants were told that while the tone was playing they were to move the response wheel forward (away from them) if they heard the loudness rise and to move the response wheel backward (toward them) if they heard the loudness fall. They were instructed that their task was to mimic any changes in loudness they heard by moving the response wheel a similar amount in the appropriate direction. Six practice trials were given to ensure that participants understood what was meant by "loudness change" and how to operate the response wheel. Responses to rising stimuli were scored by recording the highest point of the participant's response wheel movement (peak loudness rise). Responses to falling stimuli were scored by recording the lowest point of the participant's response wheel movement (peak loudness fall). The onset time of each loudness change (the time of first wheel movement) was also recorded.

Results and Discussion

The results of Experiment 1 are shown in Figure 2. An analysis of variance (ANOVA) showed a significant main effect for frequency change, $F(2, 30) = 50.41$, $p < .001$, partial $\eta^2 = .77$, and intensity change, $F(2, 30) = 89.23$, $p < .001$, partial $\eta^2 = .86$, and a significant interaction between frequency and intensity, $F(4, 60) = 4.04$, $p < .01$, partial $\eta^2 = .21$.[1] A polynomial test of order showed a significant linear trend for frequency, $F(1, 15) = 54.98$, $p < .001$, and a significant linear trend for intensity, $F(1, 15) = 97.73$, $p < .001$. An ANOVA for onset time across the nine conditions revealed no significant differences in loudness change onset as a function of intensity, $F(2, 16) = 1.5$, $p > .05$, or frequency, $F(2, 16) = 0.52$, $p > .05$. One surprising finding that ran counter to our hypothesis was that loudness was significantly greater when intensity rose and frequency remained constant ($M = 118.69$) than when both intensity and frequency rose ($M = 101.53$), $t(15) = 2.97$, $p < .01$. Future work will help to determine if this is a spurious finding or a consistent characteristic of dynamic loudness perception.

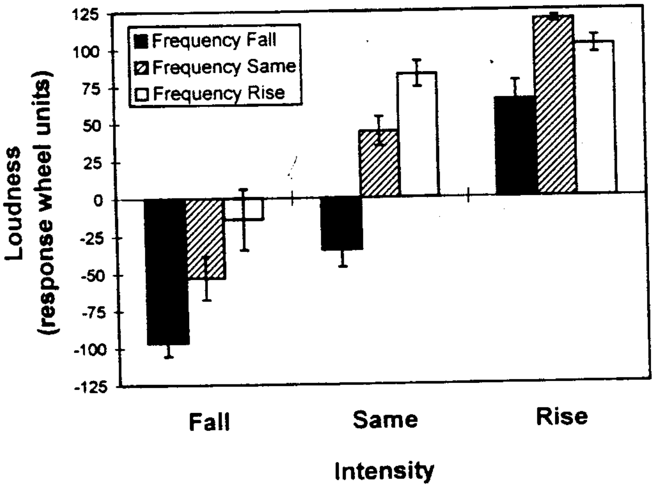

Figure 2. Perceived changes in loudness (in response wheel units) for each condition in Experiment 1. Dynamic change in frequency and intensity jointly contribute to loudness change. Error bars represent ±1 *SE*.

We were also interested in whether there would be differences in the magnitude of loudness change for rising versus falling stimuli. To compare the magnitude of loudness change across conditions regardless of whether loudness rose (represented by positive values) or fell (represented by negative values), we converted all scores to their absolute values. An ANOVA on the converted scores showed a significant effect for both frequency, $F(2, 30) = 3.85$, $p < .05$, partial $\eta^2 = .42$, and intensity, $F(2, 30) = 23.94$, $p < .001$, partial $\eta^2 = .62$. Across all conditions of frequency, the mean score for loudness rise was 97.72 ($SD = 31.15$; all scores are in response wheel units), and the mean score for loudness fall was 76.82 ($SD = 42.56$). Thus, given the same amount of intensity change, listeners generally perceived a greater change in loudness when intensity rose than when it fell. Collapsing across all conditions of intensity change, the mean score for rising frequency was 83.67 ($SD = 37.60$), and the mean score for falling frequency was 71.63 ($SD = 41.66$). Thus, rising frequency affected judgments of loudness change more than falling frequency. These results are consistent with previous work showing a preferential detection of rising pitch given rising and falling frequency and intensity stimuli (Neuhoff & McBeath, 1996).

In a natural listening environment, a sound source that gets louder can signal that the source is getting closer to the organism. A source that gets quieter can signal that the source and organism are getting farther apart. The approach of a sound source can be an environmentally important event, potentially signaling a threat or opportunity. The recession of a source would seem to be somewhat less important. Thus, the behavioral bias toward rising intensity found here and in Neuhoff and McBeath (1996) may reflect the relative importance of rising and falling intensity in a natural environment and perhaps specific neural mechanisms that respond preferentially to rising versus falling intensity (Neuhoff, 1998). This bias for rising stimuli may

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[1] Partial η^2 is a measure of the effect size for factorial designs. The statistic gives the proportion of variance accounted for with the effects of the other variables partialed out. Partial $\eta^2 = [(dfh)(F)]/[(dfh)(F) + dfe]$, where dfh = hypothesis degrees of freedom, dfe = error degrees of freedom, and F = F test statistic (SPSS, 1991).

also explain the significant rise in loudness heard when both frequency and intensity remained constant, $t(15) = 4.51$, $p < .01$.

The results of Experiment 1 show that dynamic change in both frequency and intensity jointly contributed to the perception of loudness change. In the absence of intensity change, rising and falling frequency were sufficient to elicit judgments of rising and falling loudness, respectively. Our previous work has shown that dynamic intensity change can influence perceived changes in pitch in a similar manner (Neuhoff & McBeath, 1996). The current results, taken together with the results of Neuhoff and McBeath, suggest a dynamic interacting relationship between the dimensions of pitch and loudness. Dynamic change in the unattended dimension systematically influences dynamic perception in the dimension of interest.

Interacting perceptual dimensions have typically been identified by performance with static stimuli on Garner's (1974) set of converging operations. However, in a natural environment, many stimulus dimensions, such as pitch and loudness, are dynamic. In Neuhoff and McBeath (1996), our results demonstrated the influence of dynamic intensity change on pitch, and in the present study, our results demonstrate the reciprocal influence of frequency change on loudness. Our findings suggest that a broader, more ecologically valid definition of interacting dimensions should include the influence of dynamic change in an unattended dimension on perceived change in the attended dimension.

Loudness perception under static conditions is also a function of the fundamental frequency of a tone, as is evidenced by the classic equal-loudness contours (Fletcher & Munson, 1933). A possible alternative explanation for the results of Experiment 1 is that the higher frequency tones simply sounded louder because listeners were more sensitive to the higher frequencies that we presented. For example, if a static 1047-Hz tone sounds louder than a 988-Hz tone, then we might expect that sweeping frequency from 1047 Hz to 988 Hz, as was done in Experiment 1, would result in a decrease in loudness. There would be no reason to propose a different dynamic process to explain this result. However, if there is no difference between the loudness of a static 1047-Hz tone and a static 988-Hz tone, or if the lower frequency tone is louder, then the results obtained with the dynamic tones in Experiment 1 would not be in accordance with static equal-loudness contours and would suggest dramatic differences between dynamic and static loudness perception. To test this hypothesis, we performed a control experiment using discrete static tones.

Experiment 2

In Experiment 1 we used frequency-swept tones that went from a fundamental frequency of 1047 Hz up to 1109 Hz and from 1047 Hz down to 988 Hz. If such a 1109-Hz tone actually sounds louder than a 1047-Hz tone of the same acoustic intensity, then we might expect a tone that is swept from 1047 to 1109 Hz to increase in loudness. The dynamic tones in Experiment 1 required the use of a dynamic loudness measure such as the response wheel that we used. In Experiment 2, listeners were presented with discrete static tones of the same frequencies and intensities as the initial and terminal frequencies and intensities of the stimuli presented in Experiment 1. For the static tones, a more traditional magnitude estimation procedure was used to assess the loudness of each tone.

Method

Participants. Four male and 3 female psychology students participated for course credit. All were between the ages of 18 and 22 years. None reported any hearing problems, and none had participated in the previous experiment. All were naive about the hypothesis being tested.

Stimuli. Stimuli consisted of nine square wave tones, each of three frequencies (988, 1047, and 1109 Hz) at three different intensities (70, 75, and 85 dB SPL). Spectral characteristics of the tones were the same as those in Experiment 1. All stimuli had 10-ms rise and decay times. Stimulus duration and interstimulus interval were both 3 s.

Apparatus. Stimuli were generated by a 16-bit sound card controlled by an IBM-compatible computer at a sampling rate of 44.1 kHz and were presented via Pioneer SE-205 stereo headphones. All participants were tested individually in a sound-attenuating booth.

Design and procedure. A magnitude estimation procedure was used with no standard or modulus. Each listener heard each of the nine tones four times (four blocks, nine tones per block). Tones were randomized by blocks so that no one tone was presented more than once within a block. Listeners were instructed to ignore the pitch of the tones and to assign a number to the loudness of each tone such that a tone twice as loud as another should have a number twice as large and a tone half as loud should have a number half as large. Fractions and decimals were allowed. Listeners were instructed to assign whatever number they deemed appropriate to the first stimulus. Numbers were then to be assigned to succeeding stimuli in proportion. Responses were recorded with pencil and paper.

Results and Discussion

At all frequency and intensity levels, the tested loudness was inversely proportional to the frequency of the tones (see Figure 3). The lower the frequency of the tone, the louder it was perceived to be. A 3 × 3 × 4 (Intensity × Frequency × Trial) ANOVA showed a significant main effect for frequency, $F(2, 12) = 6.47$, $p < .05$, partial $\eta^2 = .52$, and a significant main effect for intensity, $F(2, 12) = 156.87$, $p < .001$, partial $\eta^2 = .96$. The effect of trials was not significant ($F < 1$). The results support the idea that any static effect of frequency on the loudness of the tones used in Experiment 1 should oppose the effect of dynamic frequency change found. For example, if we based our predictions of dynamic perception on the results of Experiment 2, sweeping frequency from 1047 to 988 Hz should produce a signal that slightly increases in loudness and that sweeping frequency from 1047 to 1109 Hz should produce a signal that slightly decreases in loudness. Yet, in Experiment 1, we found the exact opposite. This shows that the effect of dynamic frequency change on loudness is qualitatively different from the effect of frequency that is typically illustrated in equal-loudness contours. In addition,

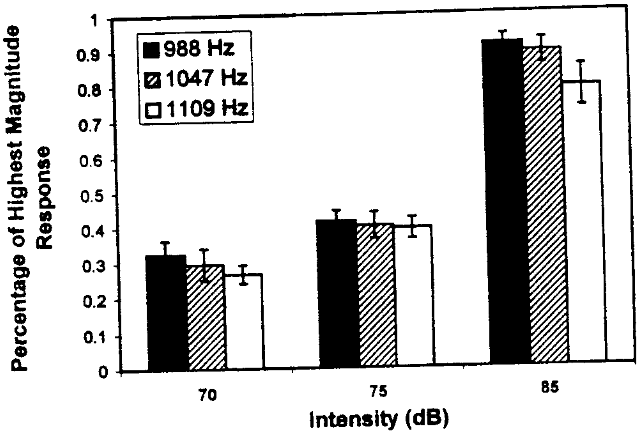

Figure 3. Results of loudness magnitude estimation for nine static tones in Experiment 2. Error bars represent ±1 *SE.*

the findings confirm a dramatic difference in the perception of loudness under conditions of dynamic versus discrete frequency change. (The results of Experiments 1 and 2 are discussed further in the General Discussion section.)

Experiment 3

In Experiment 3, we used a dichotic listening task to explore in greater detail the influence of dynamic frequency change on loudness. Specifically, we were interested in whether the physiological mechanisms responsible for the influence are central or peripheral. We also sought to test two competing models of multidimensional perception under dynamic conditions. A harmonic tone of either rising, constant, or falling frequency was presented to one ear while white noise of either rising, falling, or constant intensity was presented to the contralateral ear. Listeners tracked changes in the loudness of the noise while ignoring the dynamic harmonic tones in the opposite ear.

Previous work has suggested that equal-loudness and equal-pitch contours are a function of the peripheral auditory system (Stevens & Davis, 1938). Given the difference in loudness perception illustrated in Experiments 1 and 2, we thought that there could be different neural mechanisms or pathways that mediate dynamic and static loudness perception. Although there are obviously mechanisms in common, static sounds may not activate all of the structures that dynamic sounds do (Whitfield & Evans, 1965). The dichotic listening task might provide some preliminary information about the location of these neural structures responsible for dynamic pitch and loudness interaction. If dynamic frequency change in one ear influences loudness in the contralateral ear, then at least some of the processing responsible for the interaction of dynamic pitch and loudness perception must take place centrally, after the signals from the two ears first meet.

The dichotic listening task may also shed some light on the nature of the perceptual interaction of pitch and loudness. Previous experiments using static stimuli demonstrate that pitch influences loudness and that loudness influences pitch (e.g., Melara & Marks, 1990b). However, the nature of this influence has been debatable. The debate centers around exactly what characteristics or attributes of a multidimensional stimulus are available or can be accessed by a perceiver. Melara and Marks and their colleagues (Marks, 1989; Melara & Marks, 1990a, 1990b, 1990c; Melara et al., 1992, 1993a) have argued that the perception of pitch and loudness is an analytic process. Listeners are said to have "primary" access to each of the respective dimensions. In their view, the interaction between pitch and loudness occurs because the context created by the unattended dimension (e.g., pitch) influences judgments about the attended dimension (e.g., loudness). A high-pitched tone is perceived differently in the context of high loudness than it is in the context of low loudness.

Alternatively, the traditional model of multidimensional perception suggests that interacting dimensions are perceived holistically (Garner, 1974; Kemler, 1983a, 1983b; Kemler-Nelson, 1993; Smith & Kemler, 1977). The stimulus dimensions themselves are not directly perceived without great effort. Instead, integral stimulus dimensions are initially perceived as dimensionless, unitary "blobs" (Lockhead, 1972, 1979; Shepard, 1964). Because perceivers do not have primary access to the stimulus dimensions, they cannot selectively attend to one stimulus dimension. The perceptual experience of such a multidimensional stimulus, then, is the vector sum of the weighted values on each dimension.

Interacting dimensions have typically been defined by performance on speeded sorting, dissimilarity scaling, and categorization tasks using static stimuli. The results of Experiment 1 show that using more ecologically valid dynamic stimuli, the principles of dimensional interaction still held. However, the results of Experiment 1 would be predicted by both Garner's (1974) and Melara and Marks's (1990a, 1990b, 1990c) models of perceptual interaction. If pitch and loudness are processed holistically, then listeners would not be able to selectively attend to changes in only one dimension. Therefore, when tracking intensity change, a listener will be influenced not only by changes in intensity but also by changes in frequency. Depending on the degree to which the participant can selectively access frequency and the relative amount of change in each dimension, the holistic analysis may give way to an experience of changing loudness that does not at all depend on intensity change. Applying the case of dynamic stimuli to the model of Melara and Marks, researchers need only assume that a greater degree of dimensional change creates a more influential context. Then, perceivers who extract the stimulus attribute *constant loudness* in the context of the attribute *rising pitch* may be so influenced by the context of this rising pitch that they report rising loudness.

White noise has loudness but no detectable pitch. Thus, dichotic stimulus presentation allows the separation of pitch and loudness change. By presenting one dimension to each ear, the question of how pitch and loudness interact can be explored. If interacting multidimensional stimuli are processed holistically, then changes in the frequency of a tone presented to an unattended ear should not affect judgments about loudness change of white noise in the opposite attended ear because the tone and the noise are separate sources presented to opposite ears. However, if the context created by changing frequency in one ear is sufficient for influencing judgments about the loudness of a signal in the other ear, then the argument for contextual influence and primary access to the interacting perceptual dimensions of pitch and loudness is supported.

Method

Participants. Nine male and 15 female introductory psychology students served as participants. All were between the ages of 18 and 23 years. All were volunteers who received class credit for participation, were naive about the hypothesis being tested, and had not participated in any of the previous studies. None of the participants were professional musicians or music majors. All reported normal hearing.

Apparatus. Stimuli were generated by a 16-bit sound card controlled by an IBM-compatible PC at a sampling rate of 44.1 kHz and were presented via Pioneer SE-205 stereo headphones. Changes in frequency and intensity were controlled by the computer. Responses were made by moving a 2.5-in. (6.35 cm) stick mounted vertically in the middle of the controller wheel on an Ensoniq ESQ 1 synthesizer. The response wheel had a notched zero point, was spring loaded so that it returned to this zero point after each trial, and had a total travel of approximately 110°. All participants were tested individually in a sound-attenuating booth. Two signal lights with appropriate labels (left and right) were mounted inside the booth to designate the attended ear before each trial.

Stimuli. Stimuli consisted of either a rising, constant, or falling frequency 75-dB SPL square wave presented to one ear paired with rising, constant, or falling intensity white noise presented to the opposite ear (see Figure 4). Spectral characteristics of the tones were the same as those in the previous experiments. Square wave fundamental frequency initiated at 1047 Hz and either rose to 1109 Hz, descended to 988 Hz, or remained constant. Rising-intensity white noise began at 70 dB SPL and ascended to 85 dB SPL. Falling-intensity white noise initiated at 85 dB SPL and descended to 70 dB SPL. Constant-intensity white noise remained at 85 dB SPL. All stimuli had 10-ms rise and decay times and a duration of 3 s, with an interstimulus interval of 1.5 s.

Design and procedure. After a brief description of the difference between pitch and loudness, the experimenter gave the participants written instructions briefly outlining the procedure of the practice trials and their task requirements. Participants were then verbally instructed to listen carefully to the noise in the attended ear for any change in loudness and to ignore the sounds that occurred in the other ear. Participants were told that while the noise was playing, they were to move the response wheel forward (away from them) if they heard the loudness rise and to move the response wheel backward (toward them) if they heard the loudness fall. If no change in loudness was perceived, they were not to move the wheel at all. They were instructed that their task was to mimic any changes in loudness they heard by moving the response wheel a similar amount in the appropriate direction.

Two separate practice sessions of 20 trials each were conducted before the beginning of the experiment to ensure that the participants knew how to operate the response wheel and could recognize differences in loudness change. The first practice sessions presented only the dynamic white noise stimuli to one ear with silence in the other. The second practice session presented dynamic white noise stimuli to one ear with the square wave stimuli to the other, simulating an experimental trial.

A 3 × 3 × 2 experimental design was used with frequency (rising, constant, and falling), intensity (rising, constant, falling), and laterality (left and right) as the main factors. Participants were presented with 4 trials of each of the nine stimulus types in each ear, resulting in a total of 72 trials. Stimuli were presented randomly but were blocked by laterality. Half the participants received all of the attended stimuli for the left ear first, and the other half received all the attended stimuli for the right ear first.

Rising intensity responses were scored by recording the highest point of the participant's response wheel movement (peak loudness rise). Falling intensity responses were scored by recording the lowest point of the participant's response wheel movement (peak loudness fall). The 4 trials for each stimulus type were averaged separately for each ear yielding one average response for each stimulus for each ear.

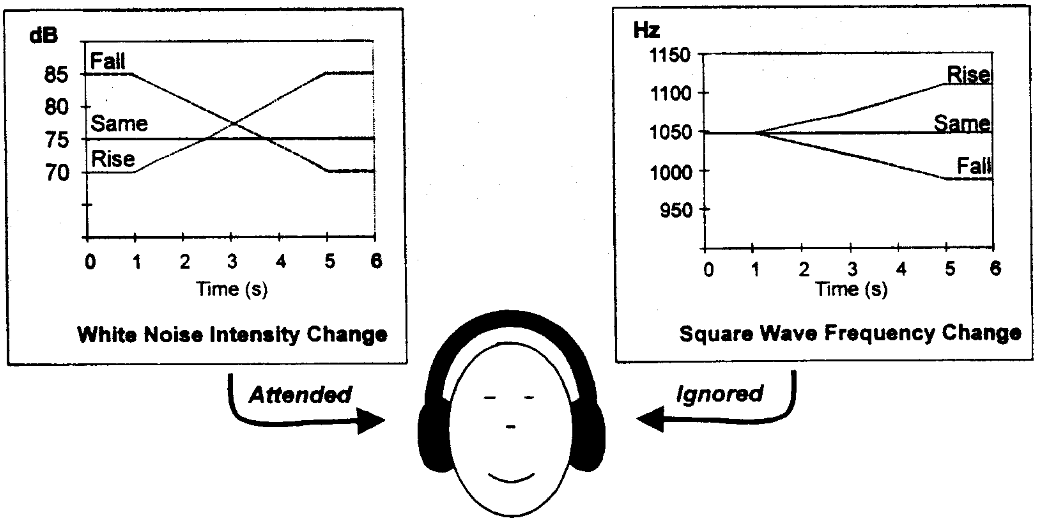

Figure 4. Stimulus conditions for Experiment 3.

Results and Discussion

A $3 \times 3 \times 2$ ANOVA showed that frequency change in the unattended ear significantly influenced loudness in the attended ear, $F(2, 46) = 14.40$, $p < .001$, $\eta^2 = .39$ (see Figure 5). When frequency rose, loudness in the contralateral ear was perceived as being higher. When frequency fell, loudness in the contralateral ear was perceived as being lower. There was a main effect of intensity change, indicating that participants could accurately track the direction of intensity change, $F(2, 46) = 282.27$, $p < .001$, $\eta^2 = .93$, and no effect of laterality, $F(1, 23) = 3.23$, $p > .05$. There was a significant interaction between frequency and intensity, $F(4, 92) = 7.22$, $p < .001$, partial $\eta^2 = .24$. Collapsing across intensity conditions, there was a significant linear trend for frequency, $F(1, 23) = 9.27$, $p < .001$ (see Figure 6). The magnitude of rising frequency responses was significantly greater than falling frequency responses, $F(1, 23) = 24.65$, $p < .001$.

The pattern of responding in Experiment 3 was somewhat unexpected given the results of Experiment 1. The interaction between frequency and intensity occurred because there was a significant loudness change difference between rising and falling frequency when intensity rose, $t(23) = 5.25$, $p < .001$, and when intensity remained constant, $t(23) = 4.92$, $p < .001$, but not when intensity fell, $t(23) = 0.43$, $p > .05$. In addition, when intensity remained constant and frequency fell, listeners still perceived a slight rise in the loudness of the noise. This appeared to be in contrast with the results of Experiment 1, in which falling frequency elicited responses of falling intensity. However, there was a dramatic difference between the stimuli presented in Experiments 1 and 3. In Experiment 1, there was a single stimulus tone that underwent simultaneous changes in frequency and intensity. In Experiment 3, there were two spatially separate signals, one presented to each ear. One changed in intensity and the other changed in frequency. Spatial location has been shown to be a salient factor in auditory stream segregation (Bregman, 1994; Bregman & Steiger, 1980; Ciocca, Bregman, & Capreol, 1992). Thus, attending to auditory signals that are spatially separated (as in Experiment 3) is generally easier than selectively attending to different auditory dimensions that occur in a single stimulus (as in Experiment 1).

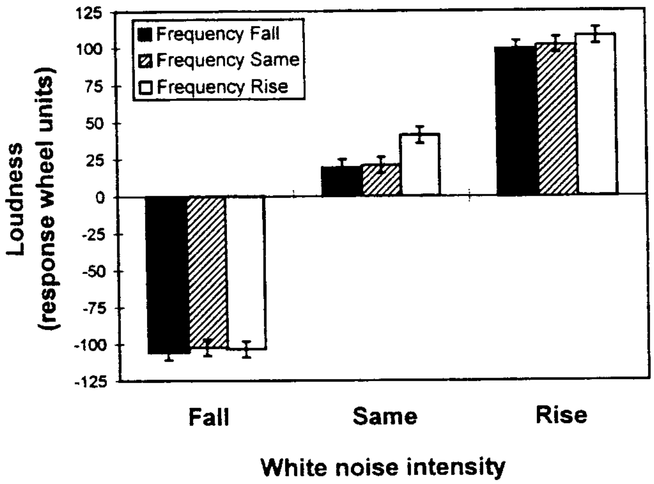

Figure 5. Perceived changes in loudness (in response wheel units) for each condition in Experiment 3. Error bars represent ±1 *SE*.

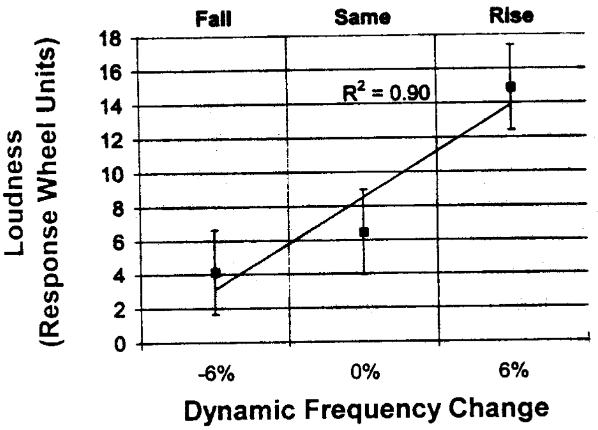

Figure 6. Results from Experiment 3. The effect of dynamic frequency change on loudness of white noise in the contralateral ear collapsed across intensity. Error bars represent ±1 *SE*.

The task in both experiments was one of selective attention. Given that the attentional task was easier in Experiment 3, perhaps it is not surprising that the effect of frequency change on loudness was somewhat diminished. Furthermore, the effects were systematically diminished more for falling stimuli than for rising stimuli. The results of Experiment 1 and those of Neuhoff and McBeath (1996) show that listeners were biased to respond to rising frequency and intensity stimuli over falling. The combination of the easier selective attention task with the bias for rising stimuli may be the reason for the pattern of responding when intensity remains constant.

There also may be some contribution of the peripheral auditory system to the dynamic interaction of pitch and loudness. Our data do not preclude this possibility. If this were the case, then that component of the peripheral auditory system that mediates the interaction between dynamic pitch and loudness would not have been active in Experiment 3. This may also account for some of the differences between the two experiments.

The results of Experiment 3 do support a conclusion that constant-intensity harmonic frequency change in one ear can influence loudness in the contralateral ear. These results provide further evidence of the interaction between pitch and loudness perception under dynamic conditions. In addition, the fact that frequency change can influence loudness in the contralateral ear suggests that at least some of the interaction between dynamic pitch and loudness perception must take place at a central neural location.

The findings also provide support for an analytic and contextually dependent processing of pitch and loudness. Because it is unlikely that participants perceived the two spatially and spectrally distinct sounds as one dimensionless blob (Lockhead, 1972, 1979), it is reasonable to conclude that the context created by changing frequency influenced loudness. The findings are consistent with the interpretation that changing frequency presented to one ear constrained the perceptual meaning of the loudness in the contralateral ear. The individual attribute of a dynamic rise in *loudness* had one perceptual meaning when paired with the attribute *falling pitch* and a different perceptual meaning when paired with the attribute of *rising pitch.* Thus, the results of the present research suggest that perceivers do have a primary access to interacting perceptual dimensions and that context created by an interacting, unattended dimension influences the phenomenal experience of the relevant dimension (Melara & Marks, 1990c; Melara et al., 1993a; Melara, Marks, & Potts, 1993b).

It may be argued that pitch and loudness are processed analytically when they occur in different acoustic signals but that they are integral and processed holistically when they occur in the same signal. However, this explanation lacks parsimony. No one debates the existence of dimensional separability, and there are clear examples of dimensions that are processed analytically. However, the Garnerian position proposes two types of processing: holistic, for interacting dimensions, and analytic, for separable dimensions. These results show that analytic processing can account for the perception of dimensions that interact in addition to those that do not. Thus, the ill-defined blob becomes unnecessary.

General Discussion

We have demonstrated that dynamic frequency change can influence loudness in a way that is qualitatively different from that which has previously been documented. Upward sweeping frequency can produce an increase in loudness, and downward sweeping frequency can produce a decrease in loudness. These effects are not predicted by static equal-loudness contours. Because frequency change in one ear can influence loudness in the other, at least some degree of dynamic pitch–loudness interaction must take place at a central neural location. The findings also suggest that the dynamic interaction between pitch and loudness is an analytic, contextually driven process.

The differential sensitivity of the auditory system at different frequencies (equal-loudness contours) is thought to be largely an effect of the peripheral auditory system (Gulick, 1971; Moore, 1989). Similarly, Stevens and Davis (1938) proposed that the mechanism responsible for equal-pitch contours is peripheral, specifically the result of nonlinear cochlear responding. The static loudness differences found between different frequency tones of the same intensity in Experiment 2 confirm this well-known effect. However, the results of Experiments 1 and 3 show that the interaction between pitch and loudness under dynamic conditions was dramatically different in two ways: First, the effect of dynamic frequency change was in the opposite direction of the effect of static frequency differences. This means that the dynamic effect had to be robust enough to overcome the static equal-loudness contour function. Second, the effect could be obtained when dynamic frequency and intensity stimuli were presented to opposite ears, precluding any peripheral mechanism as a necessary condition for the effect.

Melara and Marks (1990a) proposed a triplex model of auditory processing in which higher level auditory channels responsible for processing pitch, loudness, and timbre display a degree of perceptual cross-talk. They suggested that a listener attending to loudness might experience cross-talk from pitch that leaks into the attended stream and influences perception and performance when tracking loudness. Although Melara and Marks made no mention of whether these proposed channels are central or peripheral, our results suggest that if they do indeed exist, the channels that process the interaction of frequency and intensity are located centrally and are reciprocal in their cross-talk effects. This is not to say that pitch and loudness do not interact in the peripheral auditory system but that the peripheral and central interactions appear to be qualitatively different in their treatment of frequency and intensity information.

Loudness is influenced by many factors in addition to intensity. Such factors include absolute frequency, bandwidth, duration, intermittency, masking, perceived effort of production, and even the stimulus context in which loudness judgments are made (Marks, 1992; Rosenblum & Fowler, 1991; Scharf & Houtsma, 1986). The current research adds dynamic frequency change to the list of factors that affect loudness. The complexities of modeling loudness perception are such that even the most coherent current models of loudness perception principally describe static perception and are not predictive of dynamic perception.

As has been demonstrated here and elsewhere, there are distinct differences between dynamic and static loudness perception (Canévet & Scharf, 1990; Schlauch, 1992). Thus, the utility of a static loudness model is limited for describing perception in a natural listening environment. Although a static loudness scale can be used to describe differences between dynamic loudness percepts post hoc, such models make no prediction about the existence of such differences. Given that many environmental sounds are dynamic, our results suggest that static loudness models do not adequately account for loudness perception in a natural listening environment.

Covariation of frequency and intensity occurs in information-rich signals such as speech as well as in other naturally occurring sounds (Alain, 1993; Brenner, Doherty, & Shipp, 1994; Cutler & Butterfield, 1991; Fisher & Tokura, 1995; Gaioni & Evans, 1989). In addition, there is evidence to suggest that dynamic frequency and intensity information are converted to a common neural code (Saberi & Hafter, 1995). Thus, the interaction between pitch and loudness under dynamic conditions may have evolved to take advantage of this naturally occurring covariation of frequency and intensity. Such a system may provide a selective advantage in parsing or localizing acoustic information.

The complexities of explaining loudness perception are vast. Here we have shown that dynamic frequency change can influence dynamic loudness perception independent of static frequency effects. Our findings show that static loudness perception is qualitatively different from loudness perception under dynamic conditions. We propose that the dynamic interaction between pitch and loudness is a central neural process that is contextually based and that this process has evolved to take advantage of naturally occurring covariation of frequency and intensity.

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