Sonification and the Interaction of Perceptual Dimensions: Can the Data Get Lost in the Map?

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ABSTRACT
Many sonification techniques use acoustic attributes such as frequency, intensity, and timbre to represent different characteristics of multidimensional data. Here we demonstrate a perceptual interaction between changes in pitch and loudness, as well as perceived asymmetries in directional change. Three experiments show that changes in loudness can influence judgments of pitch change, changes in pitch can influence loudness change, and that increases in loudness are judged to change more than equivalent decreases. Within a sonification of stock market data, these characteristics created perceptual distortions in the data set. The results imply that in situations where precision is critical, caution should be exercised when using lower level acoustic dimensions such as frequency and intensity to represent multidimensional data.

Keywords
Sonification, Pitch, Loudness, Perceptual Interaction, Stock Market

INTRODUCTION
A key issue in the development of effective sonification is optimizing the degree of match between the intended sonic representation of information and the perceptual experience of that information by the listener. In many sonifications, auditory variables such as loudness, pitch, and timbre are used to isomorphically represent data variables. Often two or more data variables are represented by changing two or more of these auditory parameters within one auditory stream [5].

A potential problem with this approach is that of orthogonality [5], wherein changes in one variable may influence the perception of changes in another variable. For example, numerous studies have shown that the auditory dimensions of pitch, loudness, and timbre interact perceptually [2, 3, 7, 9, 11, 12]. Changes in any of these dimensions can influence perception of changes in the others. Thus, when such variables are used to represent data values, a distorted perception of the underlying data is a potential result. Further complicating the issue is evidence suggesting that even changes within a single auditory dimension can be perceived differently based on the direction and duration of change. For example, some work has shown perceptual asymmetries in rising and falling intensity changes of equal magnitude [1, 10].

Despite the evidence for directional asymmetries in perceived stimulus change and dimensional interaction of perceptual dimensions, very little work has examined whether these phenomena remain when perceptual dimensions are mapped on to quantitative dimensions of interest in a display. For example, it may be that untrained listeners have great difficulty giving accurate estimates of change in the somewhat unfamiliar dimensions of frequency, intensity, and spectral content, but can perform the tasks more easily and accurately when the perceptual dimensions are mapped on to more familiar and concrete variables.

On a perceptual level, the interaction of auditory dimensions is thought to stem from the context created by one dimension (e.g., pitch) in which another dimension (e.g., loudness) is perceived. For example, a loud sound is perceived differently in the context created by high pitch than the context created by a lower pitch [7, 8, 12]. However, the mechanisms and processes by which perceptual dimensions interact are still a matter of some debate [3, 9]. From an applied perspective, the importance of accurately mapping data variables onto acoustic variables suggests that a greater understanding of such perceptual interaction should be pursued. Such and understanding will facilitate more effective sonification techniques, particularly in situations where precision is critical. In the present work we explore specifically the interaction of pitch and loudness in the context of sonifying stock market data.

		Intensity	
		Rising	Falling
Frequency	Rising	**UP UP**	**DOWN UP**
	Falling	**UP DOWN**	**DOWN DOWN**

Table 1.

EXPERIMENT 1

Method

Eight listeners were presented with sounds that changed concurrently in frequency and intensity (either rising or falling) for 2.5 seconds. Rising and falling frequency and intensity were crossed to create the 4 different types of sounds illustrated in the Table 1.

In all three experiments reported here, sounds were generated by a 16 bit sound card in a Pentium PC, and fed directly into Sony MDR-v600 headphones. Rising intensity change was from 60 dB to 80 dB, falling was from 80 dB to 60 dB. In Experiment 1, rising frequency was from 200 Hz to 240 Hz, falling was from 240 Hz to 200 Hz. All sounds were pulsed on and off, with 50 ms signal bursts interspersed with 75 ms periods of silence as shown in Figure 1. Each listener heard each of the four types of sounds ten times for a total of 40 trials, all presented in random order.

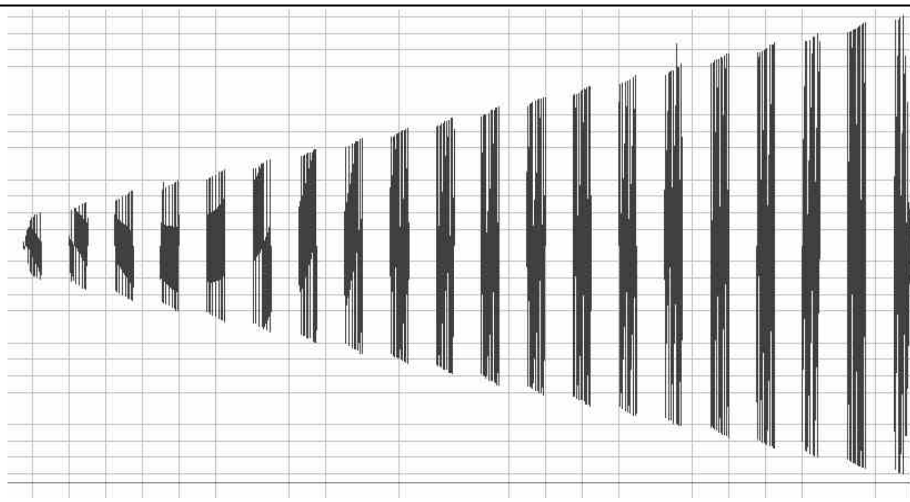

Figure 1: An example of a rising intensity stimulus.

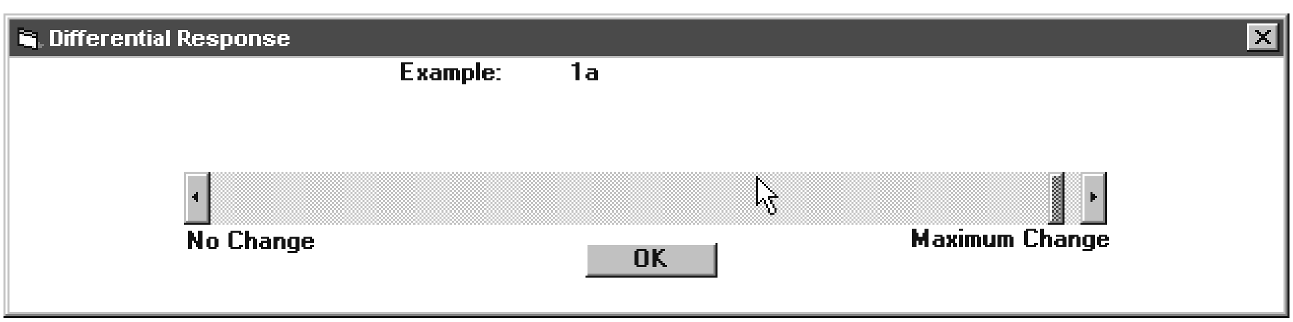

Figure 2: Visual analogue scale used to rate auditory change.

The listener's task was to indicate how much each sound appeared to change overall (in pitch and loudness combined) by moving a cursor on a computer screen to indicate the amount of change they heard in each sound (see Figure 2). Moving the cursor to the left end of the scale indicated no change, moving the cursor all the way to the right indicated maximal change. Listeners could move the cursor to any spot between the two poles. Values on the scale were unmarked but ranged from 0 to 100 for purposes of analysis.

Results

The ten responses in each condition for each participant were averaged so that each participant contributed one data point in each condition for the analysis. Despite an identical amount of physical change in each condition, an analysis of variance (ANOVA) revealed a main effect for intensity change ($F_{(1,7)}$=6.56, p=.037) indicating that sounds that increased in intensity appeared to change more than those that decreased. There was no similar main effect for frequency change ($F_{(1,7)}$=.002, p=.969). However, this was primarily due to a significant statistical interaction between changes in frequency and intensity ($F_{(1,7)}$=17.40, p=.004). When intensity rose, rising frequency sounds appeared to change more than falling. When intensity fell, falling frequency sounds appeared to change more than rising. In other words, there was a type of congruity effect. When pitch and loudness changed in the same direction, the sounds appeared to change more than when they changed in opposite directions (see Figure 3).

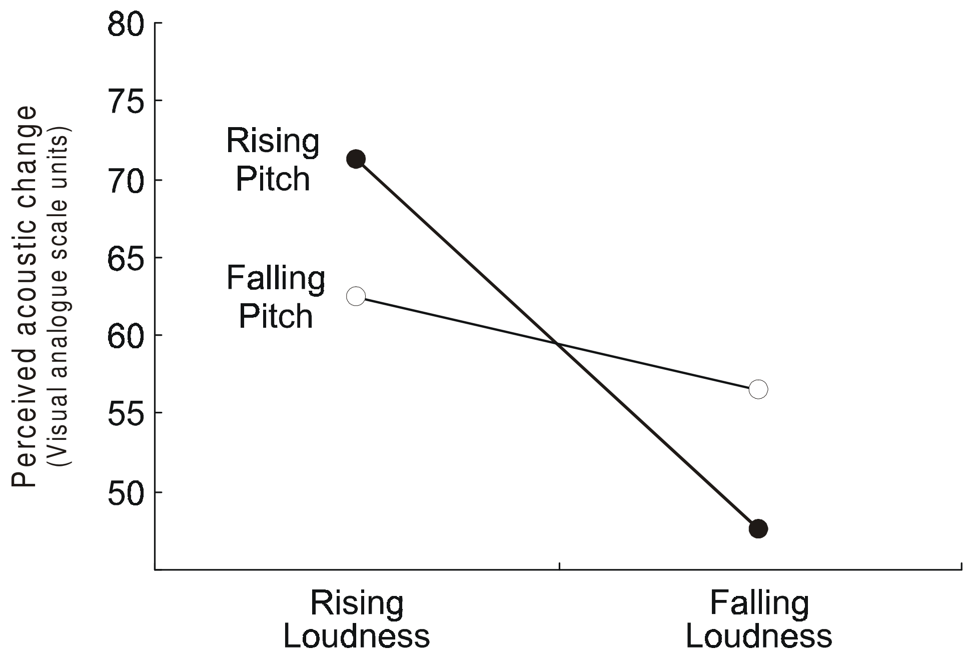

Figure 3: Average perceived change in each condition in Experiment 1. The amount of actual physical change in each condition was identical.

EXPERIMENT 2

Method

In Experiments 2 and 3 we wanted to make the listener's task more applied. We did this by assigning real world data dimensions to changes in frequency and intensity. Stimuli in Experiment 2 were identical to those in Experiment 1. However, this time the listener was told that changes in pitch represented changes in the price of a stock and that changes in intensity represented changes in the trading volume of that stock. Rising intensity denoted rising stock price, and rising intensity denoted rising trading volume. The listener's task was to listen to each stimulus and make a judgment of the final stock price and trading volume based on the changes in frequency and intensity.

Results

For judgments of stock price, we found the expected main effect for frequency change ($F_{(1,9)}$=8.69, p=.02), indicating that listeners could perform this task and that changes in pitch did indeed guide their estimates of changes in stock price. However, we also found a main effect for intensity change. ($F_{(1,0)}$=5.16, p=.05) that indicated an influence of intensity change (trading volume) on estimates of changes in stock price (see Figure 4). The results were consistent with the findings in Experiment 1. When frequency and intensity changed in the same direction, changes in stock price were perceived to be greater than when they changed in opposite directions. This occurred despite the same degree of frequency change in each condition. We found a significant main effect for intensity change on judgments of trading volume ($F_{(1,0)}$=7.12, p=.05). However, there was only a marginally significant effect of changes in stock price (frequency) on judgments of trading volume ($F_{(1,0)}$=2.04, p=.18). This is consistent with previous work that shows changes in loudness have a greater influence on perceived pitch change than do changes in pitch on judgments of loudness change [11, 12].

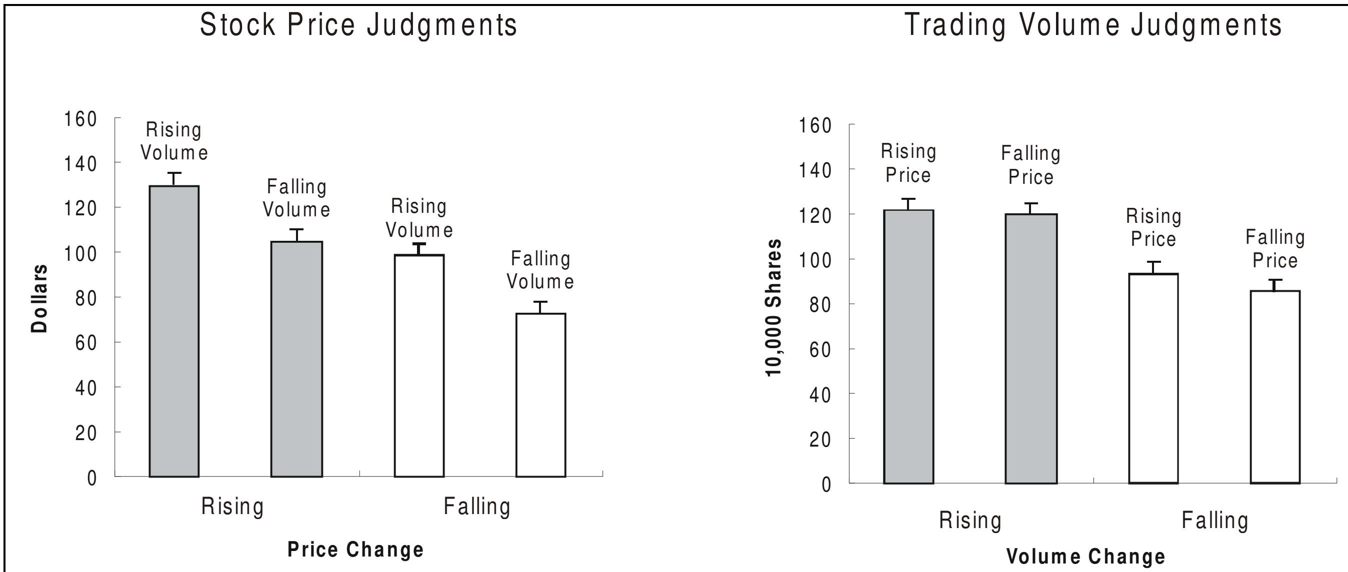

Figure 4. Results from Experiment 2.

EXPERIMENT 3

Method

In Experiment 3 we employed the same methodology that was used in Experiment 2. However, we extended the duration of the stimulus tones to 12s, and increased the variability of the changes in frequency. We used a frequency modulated tone with a center frequency that rose from 200 Hz to 300 Hz over 12s. The modulation depth was 50Hz and the rate of modulation decreased as the tone progressed. The changes were designed to more closely simulate the variability of real-time stock changes. Intensity increased or decreased by 20 dB linearly over the course of the stimulus.

Results

Once again we found results consistent with a dynamic interaction of pitch and loudness perception. For judgments of stock price, we found the expected main effect for frequency change ($F_{(1,9)}$=10.83, p=..01), indicating that changes in frequency guided estimates of changes in stock price. However, we also found a main effect for intensity change. ($F_{(1,0)}$=3.78, p=..08) that again indicated an influence of intensity change (trading volume) on estimates of changes in stock price (see Figure 5).

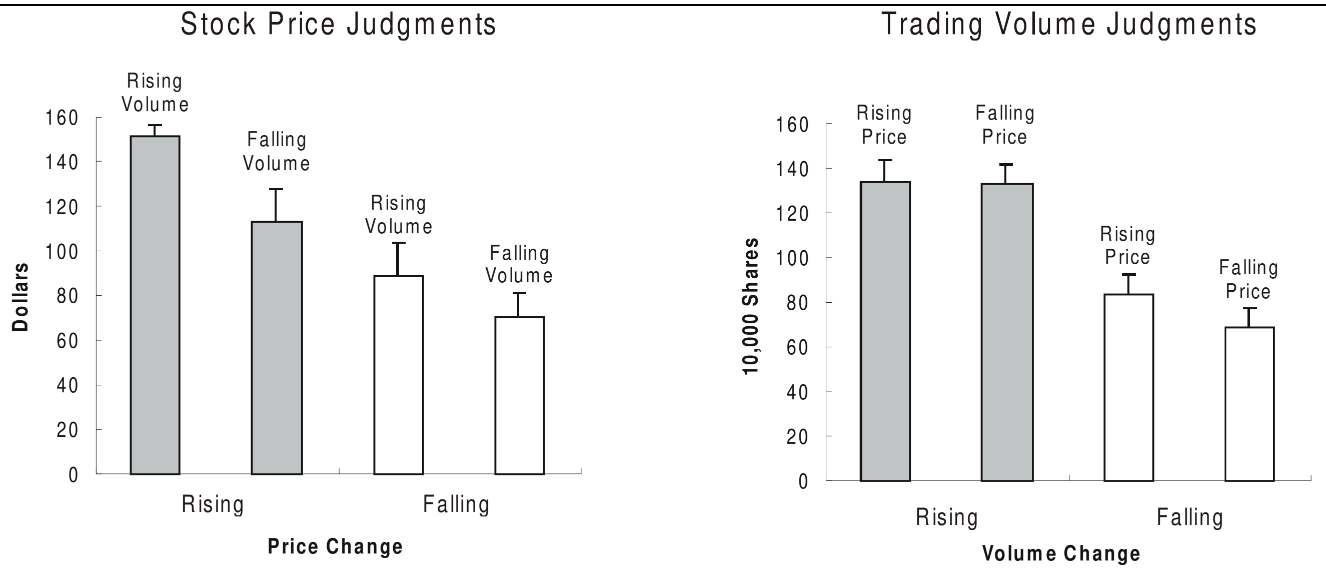

Figure 5. Results from Experiment 3.

DISCUSSION

The current results demonstrate a perceptual interaction of pitch and loudness change that has implications for sonification techniques. When frequency and intensity changed in the same direction, the perceived amount of total stimulus change was greater than when the dimensions changed in opposite directions, despite an equal amount of physical change in all conditions. This suggests that in situations where precision is critical, great care should be taken to minimize the effect of dimensional interaction on perceived changes in variables.

There was also a significant effect of direction for changes in intensity. Across the two directions of frequency change, sounds that got louder were perceived to change more than sounds that got softer. Once again, the perceptual asymmetry demonstrated with physically equivalent signals suggests that lower level acoustic dimensions such as frequency and intensity pose a potential problem for representing data with simple acoustic attributes.

In addition to the simple psychoacoustic findings of perceived asymmetries in stimulus change found in Experiment 1, there are also implications for sonification applications and sonification design theory. In Experiments 2 and 3, listeners were given a more realistic task wherein data variables were represented by changes in pitch and intensity. Although many experiments have shown that perceptual dimensions can interact, to our knowledge, this is the first study to show that when perceptual dimensions are mapped on to quantitative dimensions of interest, the interaction persists. In both experiments there was a significant influence on the dimension of interest (e.g., perceived stock price) by another simultaneously changing dimension (trading volume). There were significant differences in perceived change in cases where the physical change was identical.

One positive implication that results from these findings is that the effect of congruent acoustic changes are more salient than incongruent changes, or even acoustic change in a single dimension [12]. Thus, in situations were changes in the state of a variable are particularly critical, duplicate mapping of frequency and intensity to the same variable would likely provide improved performance [4].

Our findings are limited in that we used simulated changes in trading volume and stock prices. True market conditions produce price and volume interactions that are not as regular as the stimuli presented here. However, the results of Experiment 3 suggest that perceptual interaction persists even with stimuli that exhibit complexities and durations that far exceed those typically used in traditional psychoacoustic experiments.

Finally, although the current results are limited to dimensional interaction within the auditory domain, such interactions clearly occur in the visual domain and should be considered in the design of visual displays [13]. There is also evidence to suggest that cross modal associations and congruency effects exist between audition and other modalities [6]. Multi-modal displays are used in a variety of different environments. These associations and interactions should be explored as well in both real and virtual environments.

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