THE PERCEPTUAL CUES FOR PROCESSING TEMPORAL ORDER OF TONES DIFFERING EITHER BY FREQUENCY (SPECTRAL TOJ) OR BY PERCEIVED LOCATION (SPATIAL TOJ)

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Quantitative estimates of the ability to correctly perceive auditory temporal order (TOJ) have traditionally been measured either by the inter-stimulus interval (ISI) necessary when two tones of different frequency are presented to one ear (spectral TOJ) or by the ISI necessary when a tone to one ear is followed by the same tone to the other ear (spatial TOJ). We argue that the perceptual basis for spectral TOJ differs fundamentally from that of spatial TOJ. The latter is based on temporal discrimination; the former on frequency discrimination. First, stimulus onset asynchrony (SOA) is the major relevant variable for correct spatial TOJ ($R^2 = .97$), but not for spectral TOJ ($R^2 = .54$). Second, the effect of training on Spectral TOJ (range: 45 to 9msec) is much superior to Spatial TOJ (range: 65msec to 67msec). Third, subjects are capable of correctly discriminating spectral TOJ even when ISI=5msec, much shorter than the ISI necessary for temporal discrimination.

Temporal order judgment (TOJ) refers to the ability to correctly perceive the temporal order of at least two stimuli. The study of the human capacity to judge the temporal order of two stimuli became popular with the classic work of Hirsh (1959) and Hirsh and Sherrick (1961). A variety of different experimental paradigms have been used to study TOJ. In general, these experimental paradigms can be divided into two classes: (1) protocols in which the tones differ in their frequency (spectral TOJ) (e.g., Ben-Artzi et al., 2005; Fink et al., 2005, 2006; Kanabus et al., 2002; Szymaszek et al., 2006, 2009; Tallal, 1980); and (2) protocols in which the tones differ in the order they are presented to each (spatial TOJ) (Babkoff et al., 2005; Ben-Artzi et al., 2005; Fink et al., 2005, 2006; Szymaszek et al., 2006, 2009).

Both classes of TOJ paradigms have been used and reported in the literature for almost 60 years. The general understanding of the meaning of temporal order is that it represents a measure of the perception of the temporal relationships of two or more stimuli, and is therefore, a fairly basic indicator, or marker, of "temporality". However, the use of more than one paradigm raises the question as to whether the two paradigms are actually measuring the same perceptual mechanism, i.e., "temporality". One difficulty with this explanation is the fact that the threshold values of ISIs necessary for correct judgment of order, that are reported for the spatial vs. the spectral paradigm, are quite different. The aim of the current study was to test whether they reflect the same or different perceptual mechanism(s), by comparing the spatial and spectral TOJ paradigms with respect to: (1) the ability of the time from the onset of the first stimulus to the onset of the second one (stimulus-onset asynchrony, SOA) to predict TOJ accuracy and reaction time; (2) the extent to which the amount of training affects TOJ threshold; and (3) the ability to perform accurate TOJs with relatively short SOA (20 msec).
TOJ paradigms

Spectral TOJ. Pairs of 1kHz and 1.8kHz pure tones, were presented diotically (both to both ears). Stimulus duration of 15 msec included 1 msec rise/fall time. Participants were required to reproduce the order in which they heard the tones (high tone first then low tone, or low tone first then high tone) in a method of constant stimuli. Experimentation followed training in which the participants was familiarized with the stimuli used in the study, and with the appropriate response key for each stimulus (For more detailed description of the paradigm and its training stages see Ben Artzi et al., 2005).

Spatial TOJ. Pairs of 15 msec pure tones both at 1kHz were presented dichotically (one tone to each ear). Participants were required to reproduce the order in which they heard the tones (left ear first then right ear tone, or right ear first then left ear) in a method of constant stimuli. Experimentation followed training in which the participants was familiarized with the stimuli used in the study, and with the appropriate response key for each stimulus (For more detailed description of the paradigm and its training stages see Ben Artzi et al., 2005; Babkoff et al., 2005).

Experiment 1

Fifty-six undergraduate students (mean age = 22 years, 74% females) participated in the experiment. All participants were native Hebrew speakers. Half of the participants were randomly assigned to the spectral TOJ task, and half to the spatial TOJ task.

For both tasks, tones were presented at 60 dB SPL. Tone durations were 5, 10, 20, 30 or 40 msec and were presented with an ISI of 5, 10, 15, 30, 60, 90, 120 or 240 msec, yielding SOA values of 10-280 msec. Each ISI value was repeated 16 times, resulting in a total of 1,280 trials (2 tone orders x 8 ISIs x 5 stimulus durations x 16) per participant. After every 32 trials, participants received a short recess.

Results

The predicting value of SOA was measured using a second order polynomial curve. Plotting accuracy or RT as a function of SOA predicted 97% of the variance for the spatial TOJ paradigm, but only 54% of the variance for the accuracy data for the spectral TOJ paradigm and 62% of the RT data. A Fisher r-to-z transformation revealed a significant difference between the predicting value of the spatially-based TOJ and the spectrally-based TOJ accuracy (z=5.15, p<.001), and between the predicting value of the spatially-based TOJ and the spectrally-based TOJ RTs (z=4.8, p<.001).
Experiment 2

Thirty undergraduate students (mean age = 24 years, 42% females) performed the spatial TOJ task and 19 (mean age = 22 years, 89% females) performed the spectral TOJ task. All participants were screened for normal hearing. Absolute threshold (1 and 1.8 kHz) was measured by a two alternative forced choice 2-down-1-up adaptive staircase procedure. The threshold was the average of the last eight out of 10 reversals.

In both tasks, tone durations were 15 msec. Tones were presented at 40 dB HL. Tone pairs were presented in random order using a two alternative forced choice 2-down-1-up adaptive staircase procedure, with initial ISI of 150 msec. The experiment was terminated after 10 reversals, and the threshold was calculated as the average of the last eight reversals. The tasks were performed in two consecutive sessions.

Results

Figure 3 presents TOJ thresholds in both sessions for spectral and spatial TOJ tasks. Two-way repeated measures ANOVA was carried out with session as within subjects variable, and task as between subjects variable. Significant effect was found for session ($F_{(1,37)}=22.454$, $p<.001$), but not for task ($F_{(1,37)}=2.520$, n.s.). In addition, significant task X session interaction was found ($F_{(1,37)}=24.896$, $p<.001$). Paired-samples t-test for each task separately revealed significant difference between session 1 and session 2 in the spectral task ($t_{(8)}=3.021$, $p<.05$), but none in the spatial task ($t_{(29)}=.444$, n.s.).
Experiment 3

Thirty undergraduate students (age 21-39, 43% women) participated in the experiment. All participants were screened for normal hearing. Absolute threshold for the pure tone stimuli was measured prior to performing the TOJ tasks, as described in Experiment 2. Spectral and Spatial TOJ tasks were performed in a random order.

For both tasks, tones duration was 15 msec. Tones were presented at 40 dB SL. Tone pairs were presented with an ISI of 5, 10, 15, 30, 60, 90, 120 or 240 msec, however only data for ISI= 5 msec were analyzed for the current experiment. Each ISI value was repeated 16 times, resulting in a total of 32 trials per participant for the current analysis.

Results

Fifteen participants (50%) were able to correctly identify the order of the tones in the spectral TOJ paradigm at ISI= 5 msec (at 75% accuracy or better). However, only one participant (3%) succeeded in identifying the order of the tones at ISI= 5 msec in the spatial TOJ paradigm (Figure 4). This difference was significant ($\chi^2(1)=26.13, p<.001$).

Discussion

The purpose of the current study was to gather evidence to test the hypothesis that spectral and spatial TOJ paradigms reflect different perceptual mechanisms. Whereas the spatial TOJ paradigm taps the perception of "temporality", the spectral TOJ paradigm taps into a different perceptual mechanism. We found that (1) the overall amount of variance explained by SOA in the spatial TOJ paradigm is significantly greater than that explained by SOA in the spectral TOJ paradigms; (2) Spectral TOJ threshold estimates measured by two-alternative forced-choice procedure improved significantly from the first session to the second (reduced to 20% of the first estimate), while spatial TOJ threshold remained exactly the same from the first to the second session; and (3) while 50% of the participants were able to correctly judge spectral
TOJ with the identical SOA of 20 msec, most if not all participants are unable to accurately judge spatial TOJ with SOA= 20 msec.

The findings of the three studies provide strong evidence that spectral and spatial TOJ reflect two distinctive perceptual mechanisms. The almost total explanation of the variance of the spatial TOJ data by SOA and the poor to moderate explanation of the variance by the same SOA values for the spectral TOJ data (Experiment 1), the absence of a session to session learning effect on TOJ threshold compared with the very significant reduction in threshold from session to session learning with the spectral TOJ paradigm (Experiment 2), and an inability to accurately judge spatial temporal order with SOA= 20 msec, compared with the ease of spectral temporal order judgment at that SOA (Experiment 3) together provide evidence of different, distinctive judgments for performing the two paradigms. We conclude that temporal disparity, or "temporality", is the main, or even only cue for judging spatial TOJ; while some other perceptual mechanism (perhaps frequency-related) is the main cue for spectral TOJ, although "temporality" may serve may serve as a subsidiary cue in some circumstances.
References


