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Citation: The Journal of the Acoustical Society of America **133**, EL346 (2013); doi: 10.1121/1.4798378
View online: http://dx.doi.org/10.1121/1.4798378
View Table of Contents: http://asa.scitation.org/toc/jas/133/5
Published by the Acoustical Society of America

Evidence for a spatial bias in the perception of sequences of brief tones

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Abstract: Listeners are unable to report the physical order of particular sequences of brief tones. This phenomenon of temporal dislocation depends on tone durations and frequencies. The current study empirically shows that it also depends on the spatial location of the tones. Dichotically testing a three-tone sequence showed that the central tone tends to be reported as the first or the last element when it is perceived as part of a left-to-right motion. Since the central-tone dislocation does not occur for right-to-left sequences of the same tones, this indicates that there is a spatial bias in the perception of sequences.

PACS numbers: 43.66.Mk, 43.66.Rq [QJF]
Date Received: December 29, 2012 **Date Accepted:** March 13, 2013

1. Introduction

The inability of listeners to identify the order of brief heterogenous sounds within a sequence is well known (Warren *et al.*, 1969). Bregman and Campbell (1971) used recycling tonal sequences to show how the temporal order was more easily identified when the tones were belonging to the same frequency range. Authors called this process "auditory stream segregation." Many later experiments helped clarifying the roles of direct identification (labeling) of components and global pattern recognition in serial order retention and discrimination (for a review, see Warren, 2008).

Actually, the perception of order in sequences of discrete stimuli has been catching the interest of many scientists (including W. Wundt, V. Benussi, and E. Rubin) for nearly two centuries. Vicario (1962, 1963, 2003) provided an extensive and detailed account of the discrepancies between phenomenal and physical time in the perception of tone sequences. His experiments in the early 1960s had great importance for the construction of a theory of psychological time (Vicario, 2005) and anticipated some of Bregman's findings (Vicario, 1960, 1965). At the center of these studies on the perception of time is the phenomenon of temporal dislocation, which occurs when the reported temporal positions of events are inconsistent with their physical positions. For sequences of brief sounds, the perceived order of the elements can be different from physical order.

Vicario used two main types of stimuli in the form A1-B-A2:

(1) Two different low-pitched tones interrupted by a noise burst;
(2) Two different low-pitched tones interrupted by a high-pitched tone.

Vicario labeled as "positive dislocation" those cases when the subject perceived the middle element after the sequence of low-pitched tones and "negative dislocation" when the middle element was reported to occur before the sequence of low-pitched

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tones. While the factors of tone durations and frequencies were thoroughly analyzed by Vicario (1963), the possibility of a space-induced temporal dislocation has never been investigated. This is particularly interesting in the light of studies on asymmetries in apparent motion. In remembering or imagining a sequence of events with different locations there is a bias toward the left-to-right direction, independently of the actual direction of movement (Halpern and Kelly, 1993). A directional bias was found in the mental representation of situations in which a subject is exerting agency over an object (spatial agency bias), and it is largely attributed to culturally determined reading habits (Maass and Russo, 2003; Maass *et al.*, 2009). The spatial bias also emerged in the behavioral reaction to words referring to temporal concepts when presented to the left or right of a screen (Santiago *et al.*, 2007).

The central question of this communication is whether there is a spatial asymmetry in temporal dislocation or, more precisely: can the left-to-right spatial bias modulate temporal dislocation?

To answer this question, we made direct use of Vicario's stimuli and results. In particular, we investigated the sequences of three tones A1-B-A2 for which an equal number of positive and negative dislocations were observed. These sequences are here considered neutral as to the effects of dislocation (temporal neutrality). By playing the tones dichotically in all possible combinations of lateralization, we aimed at verifying if the temporal neutrality was affected by how the sequence unfolds in space. Driven by the studies on asymmetries and spatial biases, we hypothesized that an apparent motion of the stimuli from left to right would facilitate temporal dislocation.

2. Experiment

2.1 Method

2.1.1 Participants

Eighteen undergraduate Italian students (11 females) of the University of Padova participated in the experiment. The mean age of the participants was 29 years old (SD = ±9.3 years). None of the participants reported hearing loss or other hearing difficulties. All listeners were naive as to the purposes of the experiment.

2.1.2 Apparatus

We implemented our experiment in MATLAB (Mathworks©) using the Psychophysics Toolbox (Brainard, 1997; Pelli, 1997) and the MLP toolbox (Grassi and Soranzo, 2009). The software was running on a Pentium IV computer. Sounds had a sample rate of 44.1 kHz and a resolution of 16 bits. The output of the soundcard (M-AUDIO Fast Track Pro) was delivered to Sennheiser HD 280 pro headphones. The experiment was conducted in a silent [below 35 dB (A) at the listener's ear] room. During the experiments, the sounds' pressure at the listener's ear was approximately 60 dB SPL.

2.1.3 Stimuli

The stimulus consisted in a sequence of three pure tones of 75-ms each: A low-pitched tone followed by a high-pitched tone, finally followed by a low-pitched tone. The tones' frequencies were 92.5 Hz (F#2), 1175 Hz (D6), and 82.4 Hz (F2), respectively. Tones were temporally contiguous (i.e., separated by no temporal gap) and were gated on and off with two 7.5-msec raised cosine ramps but were otherwise constant in level. The individual tones of the sequence were presented either at the left or at the right ear of the participant. In particular, all the possible eight combinations of the three tones' locations were created (i.e., left-left-left, left-left-right, left-right-left, left-right-right, right-left-left, right-left-right, right-right-left, right-right-right). In addition, subjects listened to a sequence where all tones were presented diotically (same signal to both ears). The diotical sequence corresponds to sequence number 131 in Vicario (1963), for which an equal number of positive and negative dislocations were observed.

This last stimulus will be considered as the control stimulus in the discussion of the results.

2.1.4 Procedure

The nine sequences were presented 16 times each during the experiment in random order. The subjects listened to the sequence and reported the temporal position of the highest-pitched tone within the tone triplet, i.e., whether this tone was presented before the low-pitched tones (this response was coded as -1), in the middle of the low-pitched tones (this response was coded as 0), or at the end of the low-pitched tones (this response was coded as 1). The subjects communicated orally the response to the experimenter. Note that here we did not ask the subject to respond with the keyboard to prevent the spatial disposition of the response-keys from suggesting or biasing the subject's response.

2.2 Results

The responses were averaged over the 16 repetitions for each subject and each stimulus. The resulting quantity indicated the averaged perceived temporal position of the high-pitched tone relatively to the low-pitched tone pair. The procedure had a full-factorial design, with the nine different sequences as the within-subject factor, and the perceived temporal position as the dependent variable.

Data were submitted to an analysis of variance. Results are represented in Fig. 1. All statistics are reported in the text after Geisser-Greenhouse correction for violation of sphericity. The main effect of the sequences was significant [$F(8,136) = 7.242$, $p < 0.001$, $\eta_p^2 = 0.30$]. A one-sample *t*-test showed that the perceived temporal position of the control sequence (center-center-center) was not significantly different from 0 [$M = 0.08$, $t(17) = 1.052$, $p = 0.308$]. Orthogonal contrasts showed that only sequence left-right-right resulted in a positive dislocation [$M = 0.32$, $F(1,17) = 6.502$, $p < 0.05$] and sequence left-left-right resulted in a negative dislocation [$M = -0.33$, $F(1,17) = 20.441$, $p < 0.001$] when compared to the control.

2.3 Discussion

We did not observe any prevalent dislocation for the control stimulus, thus confirming Vicario's (1963) results. Vicario reported, for the same stimulus and 15 subjects (no

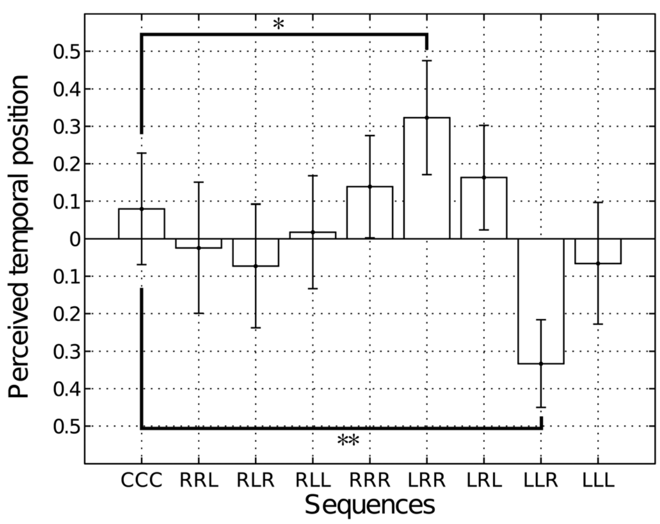

Fig. 1. Average perceived temporal dislocation for the nine sequences used in the experiment. C = center (i.e., diotic listening condition), L = left, R = right. For the contrast analyses, * is $p < 0.05$; ** is $p < 0.01$. Vertical bars represent the 95% confidence interval.

repetitions), a perfect balance of five positive dislocations and five negative dislocations. In fact, no significant dislocation was observed for most of the dichotic sequences. Significant dislocation only occurred when the two low-pitched tones composed a left-to-right motion: positive dislocation was observed for the left-right-right sequence and negative dislocation was observed for the left-left-right sequence. This result indicates that a spatial bias affects the phenomenon of temporal dislocation. Only stimuli with a left-right motion of the low-pitched tones resulted in temporal dislocation. The high-pitched tone was dislocated at the end of the sequence when played to the right, at the beginning of the sequence when played to the left. These results are consistent with the idea that there is a bias toward motion initiating on the left and ending up on the right. When the two low-pitched sequences create a left-to-right motion, the high-pitched tone is attracted toward the *temporal* position of the low-pitched tone *spatially* located on the same side. When the high-pitched tone is played to the left ear, it is attracted to the temporal position of the low-pitched tone played to the left ear: It is attracted toward the beginning of the sequence. When the high-pitched tone is played to the right ear it is attracted to the temporal position of the low-pitched tone played to the right ear: It is attracted toward the end of the sequence. Strikingly, the effect is not observed with right-to-left sequences. This asymmetry itself supports the hypothesis of a spatial bias affecting the perception of auditory sequences.

The bias is consistent with the mapping between past time and left space, and future time and right space, as evidenced by behavioral reactions (reaction time and accuracy in categorization) to time-related words displayed on the left or the right hand side of a display (Santiago *et al.*, 2007). Grondin and Plourde (2007) found that temporal intervals in a sequence were perceived as longer when the sequence was unfolding from left to right. A direction-induced stretching or shrinking of temporal interval can indeed give a partial justification of the results of Fig. 1.

Could this bias be similar to the spatial agency bias of “push” and “pull” actions reported by Maass and Russo (2003) and Maass *et al.* (2009)? To affirm that the phenomenon discovered here is a spatial agency bias one should attribute roles of subject and object, or cause and effect, to the component tones. Such a labeling may sound arbitrary, unless we refer to physical situations where similar acoustic experiences can actually occur. For example, a rolling ball that hits a second ball and launches it into motion would produce a sequence of two rolling noises interrupted by an impact noise. Under this analogy, a causal binding of the sequence of sounds is easily made. In a left-to-right sequence, the fact that the central sound tends to be perceptually delayed when presented to the right, and anticipated when presented to the left may be interpreted as an implicit association of it to the effects or to the causes, respectively. At the moment, this spatial agency interpretation is highly speculative and needs further investigations.

Acknowledgments

The authors would like to thank Leonardo Gottardo for helping us with the data collection, an anonymous reviewer for relevant suggestions, and Giovanni B. Vicario for insightful discussions and inspiration.

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