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Temporal order perception of auditory stimuli is selectively modified by tonal and non-tonal language environments ☆

Yan Bao [a,b,*,1], Aneta Szymaszek [c], Xiaoying Wang [a], Anna Oron [c], Ernst Pöppel [a,b], Elzbieta Szelag [b,c,1]

[a] Department of Psychology & Key Laboratory of Machine Perception (MoE), Peking University, Beijing 100871, PR China
[b] Human Science Center & Institute of Medical Psychology, Ludwig Maximilian University Munich, 80336 München, Germany
[c] Laboratory of Neuropsychology, Nencki Institute of Experimental Biology, 02-093 Warsaw, Poland

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ABSTRACT

The close relationship between temporal perception and speech processing is well established. The present study focused on the specific question whether the speech environment could influence temporal order perception in subjects whose language backgrounds are distinctively different, i.e., Chinese (tonal language) vs. Polish (non-tonal language). Temporal order thresholds were measured for both monaurally presented clicks and binaurally presented tone pairs. Whereas the click experiment showed similar order thresholds for the two language groups, the experiment with tone pairs resulted in different observations: while Chinese demonstrated better performance in discriminating the temporal order of two "*close frequency*" tone pairs (600 Hz and 1200 Hz), Polish subjects showed a reversed pattern, i.e., better performance for "*distant frequency*" tone pairs (400 Hz and 3000 Hz). These results indicate on the one hand a common temporal mechanism for perceiving the order of two monaurally presented stimuli, and on the other hand neuronal plasticity for perceiving the order of frequency-related auditory stimuli. We conclude that the auditory brain is modified with respect to temporal processing by long-term exposure to a tonal or a non-tonal language. As a consequence of such an exposure different cognitive modes of operation (analytic vs. holistic) are selected: the analytic mode is adopted for "*distant frequency*" tone pairs in Chinese and for "*close frequency*" tone pairs in Polish subjects, whereas the holistic mode is selected for "*close frequency*" tone pairs in Chinese and for "*distant frequency*" tone pairs in Polish subjects, reflecting a double dissociation of function.

1. Introduction

Temporal information processing plays an important role in cognitive processes like perception, attention, working memory, movement control or language (for an overview, see Fingelkurts & Fingelkurts, 2006). One domain of temporal processing is related to sequential timing in the range of some tens of milliseconds (Fink, Churan, & Wittmann, 2006; Pöppel, 2009; Szymaszek, Sereda, Pöppel, & Szelag, 2009). In order to discriminate accurately the temporal order of two successively presented stimuli, independent of stimulus modality (auditory, visual, or tactile) a

* Corresponding author. Address: Department of Psychology, Peking University, 5 Yiheyuan Road, Beijing 100871, PR China. Tel.: +86 10 62753200; fax: +86 10 62761081.

E-mail addresses: baoyan@pku.edu.cn (Y. Bao), a.szymaszek@nencki.gov.pl (A. Szymaszek), wangxiaoy@pku.edu.cn (X. Wang), a.oron@nencki.gov.pl (A. Oron), Ernst.Poeppel@med.uni-muenchen.de (E. Pöppel), szelag@nencki.gov.pl (E. Szelag).

[1] These authors contributed equally to this work.

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time interval of approximately the same duration is required between the onsets of the two stimuli (Hirsh & Sherrick, 1961). This minimum time interval is termed as *temporal order threshold* (*TOT*), which indicates a necessary temporal interval for establishing the before–after relationship of successive stimuli. A lower TOT indicates better temporal order processing.

Previous studies have revealed a number of factors that can influence TOT such as age, gender, stimulus type or presentation mode. Young children usually have difficulties to perform the temporal order task and their TOTs tend to decrease as they grow older (Berwanger, Wittmann, von Steinbüchel, & von Suchodoletz, 2004). Compared to young adults, elderly people usually demonstrate higher TOTs (Kolodziejczyk & Szelag, 2008; Szymaszek, Szelag, & Sliwowska, 2006; Ulbrich, Churan, Fink, & Wittmann, 2009). Men tend to have lower TOT than women for discriminating two identical clicks, each being presented to one ear (Lotze, Wittmann, von Steinbuchel, Pöppel, & Roenneberg, 1999; Wittmann & Szelag, 2003). Compared to monaurally presented clicks, binaurally presented tones usually result in lower TOT as observed in various subjects groups (Fink, Ulbrich, Churan, & Wittmann, 2006).

Although several factors influencing TOT have been addressed, no sufficient evidence is available regarding whether speech experience itself can influence TOT. This question is important since a close link between temporal information processing and language capabilities has been suggested in previous research. Children with language learning impairment and patients with acquired aphasia or dyslexia often demonstrate both language disabilities (e.g., deficits in phoneme identification and/or discrimination) and deteriorated timing (e.g., increased TOT for detecting the temporal order of sequentially presented acoustic stimuli) (Ben-Artzi, Fostick, & Babkoff, 2005; Gaab, Gabrieli, Deutsch, Tallal, & Temple, 2007; Sidiropoulos, Ackermann, Wannke, & Hertrich, 2010; Szelag, von Steinbüchel, & Pöppel, 1997; Tallal, Merzenich, Miller, & Jenkins, 1998; Tallal et al., 1996; Vandermosten et al., 2011; Wittmann & Fink, 2004). Based on these observations temporal order processing as an underlying basis for language comprehension is assumed. However, a reversed consideration might also be interesting, i.e., whether language experience may influence temporal order processing.

Apparently, only one study thus far addressed this question (Szelag et al., 2011). The results seem to suggest a common and language-independent mechanism for temporal order processing, since no language effect on TOT was observed. However, not having observed such an effect on TOT might have had several reasons. First, the subjects tested in their study were German and Polish, whose native languages are different in many aspects, but also share important similarities, since both German and Polish fall into the same category of non-tonal languages. Thus, these two languages might be not sufficiently different for capturing a potential language effect on temporal order processing. Second, the acoustic stimuli used for measuring TOT in their study were two identical brief stimuli (1 ms clicks) which are qualitatively different from two stimuli such as tones with different frequencies. Successive presentation of two tones with different frequencies mimics better the frequency variations that one experiences in a natural speech environment. Third, the two clicks in their temporal order measurements were presented monaurally with one click to one ear (e.g., left ear) and the other click to the other ear (e.g., right ear). This stimulus presentation mode is obviously different from a normal auditory environment, in which speech signals are simultaneously received from both ears.

In order to answer the question whether language experience influences temporal order processing the temporal characteristics of tonal and non-tonal languages have to be addressed in more detail. It is well known that temporal cues in speech signals play an important role in decoding syllables or words into their phonemic segments for auditory comprehension. For example, to discriminate "duck" and "tuck" in English, or "dui" and "tui" in Chinese, the *voice-onset-time* (VOT, the time distance between the burst and the onset of laryngeal pulsing) for voiced and unvoiced consonants (/d/ and /t/) plays a crucial role, since the VOT in many languages has different duration. Besides this general aspect, tonal and non-tonal languages differentiate themselves in some temporal characteristics such as the number of syllables in a word, the duration of consonants or vowels. A tonal language such as Chinese is mainly monosyllabic, while non-tonal languages such as English, German and Polish are typically multisyllabic. The duration of vowels in Chinese generally lasts longer than that in non-tonal languages. However, the most salient difference in temporal characteristics between tonal and non-tonal languages is related to pitch contour (Kann, Wayland, Bao, & Barkley, 2007; Krishnan, Gandour, & Bidelman, 2010; Luo, Boemio, Gordon, & Poeppel, 2007). Unlike non-tonal languages such as German and Polish, the meaning of a word in a tonal language such as Chinese cannot be solely defined by consonants and vowels without a lexical tone. For example, the Chinese syllable /ba/ may has four distinct lexical meanings when spoken with different pitch contours. It can mean the digit "8" when pronounced with a *high level* tone, the action "pulling up" with a *high rising* tone, the "target" for hunting with a *low dipping* tone, or the appellation "father" with a *high falling* tone. Therefore, to extract the meaning of Chinese words, the pitch contour which features small changes in frequency range plays a crucial role. In contrast, non-tonal languages such as English, Germany and Polish only have one single lexical meaning in one syllable regardless of some possible tone variations; thus, it is the pitch height, not the pitch contour, which is important in decoding semantic information. In other words, non-tonal languages are characterized by the large changes in frequency range, and the pitch contour plays barely any role in decoding lexical meanings.

Considering the limitations in the study mentioned above (Szelag et al., 2011) and the major difference between tonal and non-tonal languages as outlined above, the question of whether a language environment may influence temporal order processing has to be addressed again. Therefore, we designed two experiments in the present study. Experiment 1 aimed to replicate the study by Szelag et al. (2011) using monaurally presented clicks in two other language groups, i.e. Chinese and Polish subjects. The purpose of this experiment was to test whether the