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fMRI reveals lateralized pattern of brain activity modulated by the metrics of stimuli during auditory rhyme processing

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ABSTRACT

Our fMRI study investigates auditory rhyme processing in spoken language to further elucidate the topic of functional lateralization of language processing.

During scanning, 14 subjects listened to four different types of versed word strings and subsequently performed either a rhyme or a meter detection task. Our results show lateralization to auditory-related temporal regions in the right hemisphere irrespective of task. As for the left hemisphere we report responses in the supramarginal gyrus as well as in the opercular part of the inferior frontal gyrus modulated by the presence of regular meter and rhyme. The interaction of rhyme and meter was associated with increased involvement of the superior temporal sulcus and the putamen of the right hemisphere.

Overall, these findings support the notion of right-hemispheric specialization for suprasegmental analyses during processing of spoken sentences and provide neuroimaging evidence for the influence of metrics on auditory rhyme processing.

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1. Introduction

> "My words fly up, my thoughts remain below: Words without thoughts never to heaven go."
> (William Shakespeare, Hamlet, Act 3, Scene 3).

Despite the fact that rhyme detection is believed to be one of the earliest developing and most simple phonological awareness skills and has been linked to the development of different language functions (Coch, Grossi, Skendzel, & Neville, 2005), there exists only parsimonious knowledge about the brain organization of rhyme in spoken language. By definition a rhyme is formed by the relationship between two phonological compounds in the way that rhyming word pairs are phonologically identical from the last accented vowel to the end of a word (e.g. "hat" and "cat") (Bower & Bolton, 1969).

Rhyme, particularly when combined with a regular meter, is suggested to increase the saliency of a stimulus and thus to draw the listeners' attention toward prosodic stimuli properties – in particular rhythm, stress and intonation (Obermeier et al., 2013). Like meter, rhyme represents a pattern of recurrence and is considered to serve as a kind of structure giving device. In that way rhyme as well as a regular rhythm both provide a degree of predictability, which supports memorization. In this context, several studies were able to demonstrate a beneficial effect of rhyme and meter on cognitive processing of the stimuli. For instance it could be shown that target words rhyming with a preceding word are easier to process (Coch et al., 2005; Kramer & Donchin, 1987; Rugg, 1984a,b) and that regular metrical structure is easier to remember than an irregular metrical pattern (Essens & Povel, 1985).

During the last years, the relevance of metric cues in different domains of language processing such as speech segmentation has been investigated by an increasing amount of studies. In particular, these studies were able to give evidence to the influence of metrical cues and predictions on syntactic (Schmidt-Kassow & Kotz, 2009), phonological (Cason & Schön, 2012) and semantic processing (Rothermich & Kotz, 2013).

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Furthermore, meter and rhyme seem to have an impact on aesthetic liking and emotional involvement of the listener. In a recent behavioral study, Obermeier et al. (2013) were able to show that rhyme as well as regular meter both significantly contribute to the aesthetic and emotional perception of poetry. Rhyming verses yielded more positive ratings than non-rhyming ones. Of pertinent interest in the context of the present study is also that the positive effect of rhyme was stronger in strophes with pseudo-words.

The empirical investigation of rhyme processing is of interest from different perspectives. From a neurodevelopmental point of view, rhyme awareness is considered as one of the earliest developing forms of phonological awareness (Davids, van den Brink, van Turennout, & Verhoeven, 2011; Vloedgraven & Verhoeven, 2007). Behavioral studies were able to show not only that auditory rhyme detection skills develop early in life but also that rhyme awareness can serve as a predictor for later language skills such as learning to read (Avons, Wragg, Cupples, & Lovegrove, 1998; Bradley & Bryant, 1983; Bryant et al. (1989); Goswami, 1993; Wood & Terrell, 1998). In line with this, dyslexic children and adults exhibited increased difficulties in rhyme detection tasks (Rumsey et al., 1992).

In order to be able to accurately detect rhyme on sentence-level, phonetic information needs to be memorized until the critical phoneme is encountered and the comparison with the previous item can be done. Rhyme judgments are therefore believed to engage the phonological store as well as a more active process of holding the information active through a subvocal rehearsal system (Baddeley & Lewis, 1984; Baldo & Dronkers, 2006).

From the perspective of neuropsychological research, the investigation of auditory rhyme processing on the sentence level is – in our view – of specific interest pertaining to the question of functional lateralization in speech processing. The predominance of the left hemisphere in most aspects of speech and language processing is a well-evidenced fact in cognitive neuroscience (Friederici, 2012). Yet several facets of speech perception and the processing of spoken utterances have been associated with rightward lateralization in superior temporal regions: The right posterior superior temporal area has been found to be involved in processing speech prosody (Booth et al., 2002; Hesling, Clément, Bordessoules, & Allard, 2005; Meyer, Alter, Friederici, Lohmann, & vonCramon, 2002; Meyer, Steinhauer, Alter, Friederici, & VonCramon, 2004; Zhang, Shu, Zhou, Wang, & Li, 2010) vocal timbre (Lattner, Meyer, & Friederici, 2005) as well as explicit processing of speech rhythm (Geiser, Zaehle, Jancke, & Meyer, 2008) and meter (Hurschler, Liem, Jäncke, & Meyer, 2013).

However, a simple conception of prosody as a right-lateralized brain function *per se* does not do justice to the complexity of the topic. Instead increasing evidence in the field has led to different models of hemispheric processing of prosody based on functional or physical parameters (Van Lancker Sidtis, Pachana, Cummings, & Sidtis, 2006). While so called functional models state that laterality is determined by the function of the prosodic stimulus (such as linguistic vs affective), physical models link lateralized hemispheric processing to physical stimulus properties (eg. temporal vs pitch elements). It has been argued that these two approaches are not mutually exclusive but rather contribute in varying degrees to prosodic processes and thus are able to coexist (Van Lancker Sidtis et al., 2006).

These models make predictions of variable distinctness regarding the lateralization of brain responses in different speech perception tasks. One such prediction is based on the model of "asymmetric sampling in time" (Poeppel, 2003) and states that "phonemic phenomena occurring at the level of syllables should be more driven by right hemisphere mechanisms" (Poeppel, 2003, p. 251). Considering the fact that one of the most prominent characteristics of rhymes is the repetition of the same stressed vowels and thus rhyme detection essentially relies on such phonemic segmentation processes on syllable-level, the model predicts a task-related right-lateralized activation of the posterior superior temporal gyrus (pSTG) (Poeppel et al., 1996).

As highlighted by the conceptual framework proposed by Van Lancker Sidtis et al. (2006), speech mode and task essentially influence the pattern of brain regions involved in prosodic processing – in particular lateralization and involvement of basal ganglia.

So far, neural correlates of rhyme detection have almost exclusively been investigated on word level, often in visual modality and by means of electroencephalography (EEG) methods. Event-related potential (ERP) studies were able to demonstrate, that the brain shows different responses to rhyming and non-rhyming words (Rugg, 1984a,b; Wagensveld, Segers, van Alphen, Hagoort, & Verhoeven, 2012). This effect has typically been expressed by a more negative bilateral posterior response for nonrhyming targets (Rugg, 1984a,b) as well as a more negative response at lateral sites for rhyming targets (Coch et al., 2005; Khateb et al., 2000).

In a former fMRI study (Hurschler et al., 2013) we investigated the neural basis of auditory rhyme processing on the sentence level with word strings spoken in a metrical, verse-like manner. The rhyme detection task was associated with asymmetry in temporal cluster size with a more extended cluster in the right as compared to the left posterior superior temporal gyrus (STG) as well as stronger blood oxygen level dependent (BOLD) responses in the left frontal operculum and the anterior insula for the processing of rhymed as compared to non-rhymed versed word strings.

The aims of the present study are to extend prior knowledge about the neural correlates of auditory rhyme detection, and to gain specific insight in the interaction of the degree of metrics and the presence of rhyme in auditory stimuli. In a broader sense, this study is meant to contribute to the topic of functional lateralization during speech perception, in particular in left and right perisylvian regions. The novelty of the present study particularly lies in the possibility to directly examine the influence of metricity on auditory rhyme processing.

The experimental conditions were constituted of four different types of versed word strings that systematically varied in the absence or presence of a rhyme and a regular meter. By using pseudo-words we aim to rule out possible confounding effects of semantic expectation processes.

On one hand, this design allows us to investigate the neural network generally indicative of rhyme detection on sentence-level and thus to possibly replicate findings of our first explorative study. On the other hand, in addition to our first study, it also enables us to examine whether and how brain responses are mediated by metrical and rhythmical information available in spoken sentences. Based on the findings of our first study (Hurschler et al., 2013) as well as findings of the aforementioned studies and the prediction of the "asymmetric sampling in time" model (Poeppel, 2003) we hypothesize that the task (rhyme and meter detection) should recruit bilateral circuits in the auditory temporal regions with a clear functional lateralization to the right STG. We further expect that rhyme as well as meter detection recruit areas related to verbal working memory, such as, the left inferior parietal lobe and the left frontal operculum. Finally, assuming an interaction of rhyme and meter we expect activation in these regions to vary between conditions.

2. Methods

2.1. Subjects

Fourteen right-handed native Swissgerman speakers completed the fMRI study (21–33 years, mean age = 25.3, 7 female). According to the Annett-Handedness Questionnaire (AHQ) (Annett, 1970) all participants were consistently right-handed

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