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Cross-modal comparisons of stimulus specificity and commonality in phonological processing

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ABSTRACT

Phonological processing is a fundamental ability which underlies language comprehension. Functional neuroanatomy of phonology constitutes a matter of ongoing debate. In the present study, subjects performed visual (rhyme detection) and auditory (identification of spoken words starting with a given consonant) tasks that were contrasted with matched nonverbal tasks. We identified regions critical for phonological processing which were either stimulus specific or supramodal. The results revealed a high degree of modality specificity in both visual and auditory networks. Moreover, we observed a modality independent region in the left middle temporal gyrus (MTG)/superior temporal sulcus (STS), between a more anterior temporal area with auditory specificity and a more posterior temporal area with visual specificity. This dissociation in functional neuroanatomy suggests that this area may be a core region for supramodal phonological processing, acting as a gateway between spatially separate, but stimulus specific, phonological processes and more general linguistic functions.

1. Introduction

Effective phonological processing is a fundamental ability for identifying elementary segments of spoken language, including phonemes, syllables and words (Schulte-Körne, Deimel, Bartling, & Remschmidt, 1999; Siok, Jin, Fletcher, & Tan, 2003; Wandell, Rauschecker, & Yeatman, 2012). It constitutes a critical component of language processing for mapping the sound structure in processing oral or written information onto higher levels of language representation. Phonological processing plays a central role in verbal communication and its neuroanatomical representation still remains a matter of ongoing debate. To clarify these issues, we provide a definition framework for phonological processing to help in understanding these processes and their associated cortical networks.

1.1. Definition of phonological processing skills and terminological remarks

The term phonological processing covers the range of phonological abilities underlying efficient comprehension of spoken or written language. Converging evidence suggests the existence of three highly interrelated phonological processing abilities: phonological memory, phonological access to lexical storage and phonological awareness (e.g., Anthony & Francis, 2005).

Phonological memory refers to coding information in a sound-based representation system for temporary storage. It corresponds to the phonological loop in Baddeley's working memory models (Baddeley, 2007, 2012; Baddeley & Hitch, 1974). This loop can hold acoustic or speech based information in its phonological store and maintain this material by subvocal repetition, e.g., auditory span tasks, like digit span (Anthony, Williams, McDonald, & Francis, 2007). *Phonological access to lexical storage* refers to the efficiency of retrieving phonological codes from memory. Individual differences in this efficiency are typically operationalized by performance on rapid automatic naming tasks in which numbers, letters or common objects are named as fast as possible (Anthony et al., 2007). *Phonological awareness* refers to sensitivity to the sound structure of oral language (Anthony & Francis, 2005) and constitutes the focus of the current study.

Phonological awareness manifests behaviorally in variety of language skills. It refers to recognition, discrimination and manipulation of the sounds in one's language, regardless the size of the processed word unit (Anthony & Francis, 2005; Anthony & Lonigan, 2004; Anthony, Lonigan, Driscoll, Phillips, & Burgess,

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2003). Phonological awareness encompasses *phoneme awareness*, the ability to manipulate individual phonemes in words necessary in various phonological tasks, including phoneme and syllable identification, segmenting words into single phonemes, separation and identification of the initial sound in words or syllables, phoneme counting, segmentation, sound comparison, word rhyming, phoneme matching, blending, deletion, and substitution (Høien, Lundberg, Stanovich, & Inger-Kristin, 1995; Vloedgraven & Verhoeven, 2007). It is believed that phonological awareness is strongly related to literacy across many languages (Anthony & Francis, 2005; Anthony et al., 2007; Vloedgraven & Verhoeven, 2007).

According to Anthony and Francis (2005) phonological awareness skills can be distinguished by two factors: (1) the type of task performed, and (2) the unit of word structure analyzed (syllables, onsets, rimes, or phonemes). Some authors stress the importance of stimulus modality (visual or auditory), as well as the makeup of the specific phonological task (Burton, LoCasto, Krebs-Noble, & Gullapalli, 2005). Successful phonological analysis involves other cognitive processes in addition to language, such as attention or short-term memory resources. Phonological analysis constitutes a basis for the next steps of language comprehension, including morphological processing, lexical access, syntactic and semantic processing (Friederici, 2012).

Phonological processing requires modality-specific (unisensory) information processing before creating modality independent (cross-modal, named also supramodal or amodal) percepts which may then be transferred into a short-term store (Quack, London, & Talsma, 2015). The existing terminology concerning these processes is not consistent. For example, Stein et al. (2010) use the terms 'modality-specific' *vs*. 'cross-modal' when describing properties of objects and 'unisensory' *vs*. 'multisensory' when referring to neural or behavioral processes associated with single or multiple sensory modalities. To avoid terminological confusion, in the current study we use the terms: modality-specific *vs*. supramodal.

1.2. Measures of phonological awareness

Vloedgraven and Verhoeven (2007) indicated several problems with the measurement of phonological awareness. One of them concerns the task type, and another involves the difficulty of items used to measure phonological awareness. There is some evidence that rhyming tasks appear to be the easiest, while tasks requiring phoneme manipulation appear to be the most difficult (Adams, 1990; Chard & Dickson, 1999). Another problem involves task modality. Both auditory comprehension and reading are multimodal processes that require integration of signals arriving from different sensory modalities (Quack et al., 2015) and associated transmission of information among different brain networks.

A distinction between modality specific and supramodal phonological tasks is reflected in recent neuroimaging studies (e.g., McNorgan, Awati, Desroches, & Booth, 2014; McNorgan & Booth, 2015; McNorgan, Randazzo-Wagner, & Booth, 2013). For example, Burton et al. (2005) showed that identifying the onset of the final consonant of aurally presented pseudowords revealed task-specific activity increases in BA 46/9 that were best explained with respect to additional monitoring task demands. Cohen et al. (2002) described studies by Dehaene, Le Clec'H, Poline, Le Bihan, and Cohen (2002) that used the identical 'same-different' judgment task with pairs of visual or auditory stimuli. The authors demonstrated that the visual word form area (VWFA) was engaged by strings of letters, and showed no modulation by auditory words or pseudowords, suggesting a unimodal character for the VWFA. In a series of experiments McNorgan and co-workers studied rhyming judgment in unimodal (visual or auditory) and cross-modal conditions, discovering various modality- and task-specific activity changes. For example, in McNorgan et al. (2013) participants were presented with paired stimuli. In the cross-modal condition, the first item was presented auditorily, and the second one was presented visually. This task revealed clear activity increases in the *planum temporale*, an area believed to be a critical for cross-modal integration (McNorgan et al., 2014). The roles of the *planum temporale* and posterior superior temporal sulcus (STS) were also explored in McNorgan et al. (2013). In another study, McNorgan and Booth (2015), using a similar cross-modal rhyming judgment paradigm, showed that such a task revealed sub-additive audiovisual modulation in left fusiform gyrus (FG).

The experiment reported here constitutes another approach to study modality specific and supramodal aspects of phonological awareness from a neuroanatomical perspective. We used two typical phonological awareness tasks studied in previous reports i.e., rhyming and phoneme identification. For example, rhyming was studied by Burton et al. (2005), Bolger, Minas, Burman, and Booth (2008), McNorgan et al. (2014), McNorgan and Booth (2015), whereas, phoneme identification was explored by Burton et al. (2005), LoCasto, Krebs-Noble, Gullapalli, and Burton (2004).

The description of trial structure is given in Fig. 1. The rhyming task requires phonological retrieval and maintenance (McNorgan et al., 2014). In the visual modality, reading a word requires converting orthographic representations to phonological representations. After recoding orthographic information into segmented syllables, the last syllable is maintained in verbal working memory or the phonological loop (Baddeley's model). In between, the picture of the object presented for a rhyming judgment (target stimulus) has to be identified. The rationale behind this presentation format was to aid memory. As we used easily named, well known objects, a switch from visual to phonological coding occurs. Next, the last segment of the test word held in the phonological articulation loop is compared with incoming information from the target word. On the basis of such comparisons the decision of rhyming *vs*. non-rhyming is made.

To avoid simple visual comparison during rhyming (simple orthographic pattern recognition), we presented a picture of the target word and a written test word. It should be mentioned that, in Polish, for rhymed words the rimes should be identical (e.g., gazETA – lunETA), not as in English when they may be orthographically different (e.g., got – bought). The Polish language is fairly consistent in the mapping between orthography and phonology, differing from English which is much more inconsistent (Bolger et al., 2008).

Using combined presentation, we believe that our visual rhyming task required a more complicated process than just simple visual comparison involving matching phonology. We argue that our rhyming task engages not only the phonological loop, but also the visuo-spatial sketch pad to store visual information (Baddeley, 2012).

In addition, our study used auditory task phoneme identification. It requires, during word listening, segmentation of a continuous acoustic signal and recoding of acoustic–phonetic information. Our task required separation, and then, identification of the initial consonant. Burton et al. (2005) mentioned that recoding of acoustic–phonetic information into its corresponding articulatory gestures is needed to segment consonants from vowels. This acoustic – phonetic information is maintained by subvocal rehearsal in the phonological loop or verbal working memory, and then compared with the visually presented letter.

1.3. Cortical regions associated with phonological processing – a summary of previous reports

The neural mechanisms responsible for phonological processing are not fully understood and there is an ongoing debate concerning