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Language-specific cortical activation patterns for verbal fluency tasks in Japanese as assessed by multichannel functional near-infrared spectroscopy

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ABSTRACT

In Japan, verbal fluency tasks are commonly utilized as a standard paradigm for neuropsychological testing of cognitive and linguistic abilities. The Japanese "letter fluency task" is a mora/letter fluency task based on the phonological and orthographical characteristics of the Japanese language. Whether there are similar activation patterns across languages or a Japanese-specific mora/letter fluency pattern is not certain. We investigated the neural correlates of overt mora/letter and category fluency tasks in healthy Japanese. The category fluency task activated the bilateral fronto-temporal language-related regions with left-superior lateralization, while the mora/letter fluency task led to wider activation including the inferior parietal regions (left and right supramarginal gyrus). Specific bilateral supramarginal activation during the mora/letter fluency task in Japanese was distinct from that of similar letter fluency tasks in syllable-alphabet-based languages: this might be due to the requirement of additional phonological processing and working memory, or due to increased cognitive load in general.

1. Introduction

Verbal fluency tasks have long served as a standard paradigm for neuropsychological testing of cognitive and linguistic abilities (e.g., Lotsof, 1953; Rogers, 1953), and have gained scientific as well as clinical importance in psychiatry, neurology, and nuerosurgery (e.g., Frith et al., 1995; Monsch et al., 1992; Watanabe et al., 1998). In performing verbal fluency tasks, subjects are requested to generate words, in general vocally, according to a given rule. Typically, words are generated within a particular semantic category (e.g., fruits) to form a category fluency task, or with a particular letter (e.g., E-words) to form a letter fluency task. These are often referred to as semantic and phonological fluency tasks, respectively (Lezak, Howieson, Bigler, & Tranel, 2012). An extensive meta-analysis of lesion studies revealed a differential association between verbal fluency tasks and brain regions: deficits in category fluency tasks are associated with temporal lobes, including Wernick language areas, while those in letter fluency with frontal lobes, including Broca's area as well as temporal lobes (Henry & Crawford, 2004).

There appear to be two major uses of verbal fluency tasks. First, reflecting the functional association between the verbal fluency tasks and language-related brain regions suggested by the lesion studies, the tasks are commonly used for diagnosing expressive aphasia, and have proven to be valuable tools for detecting hemispheric language dominance before neurosurgery (c.f. Watanabe et al., 1998). Second, they have been adopted to examine executive control processes in a variety of neurological and psychiatric disorders including traumatic brain injury (Henry & Crawford, 2004), depression (Wolfe, Granholm, Butters, Saunders, & Janowsky, 1987), Alzheimer's disease (Monsch et al., 1992), schizophrenia (Phillips, James, Crow, & Collinson, 2004; Saykin et al., 1991), attention deficit/hyperactivity disorder (Geurts, Verte, Oosterlaan, Roeyers, & Sergeant, 2004), and autism (Turner, 1999).

Reflecting the clinical and functional importance of verbal fluency tasks, considerable interest has been taken in elucidating the neural mechanism underlying these tasks using neuroimaging methods (Birn et al., 2010). In typical neuropsychological procedures requiring free recall of words, subjects are requested to

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overtly produce as many words as possibile within a limited time period. The tasks are performed face-to-face with experimenters to faciliate natural speech in a natural environment. This allows experimenters to monitor the task performance through direct observation and to record behavioral performance data (Birn, Cox, & Bandettini, 2004). However, typical neuroimaging environments, especially that of fMRI, do not provide an ideal environment for performing verbal fluency tasks. Moreover, fMRI measurements are often purturbed by task-related facial and orolingual motion resulting from overt speech. To reduce task-related motion artifacts, fMRI studies generally utilize covert word generation (e.g., Gurd et al., 2002; Hirshorn & Thompson-Schill, 2006; Perani et al., 2003). Alternatively, overt, single-word production paced by experimenters may be adopted (e.g., Abrahams et al., 2003; Phelps, Hyder, Blamire, & Shulman, 1997). However, covert word fluency tasks fail to provide behavioral indices, and make it difficult to interpret and validate experimental results, especially when patients are being studied (Billingsley et al., 2004; Birn et al., 2010). In addition, covert tasks may not serve as simple substitutes for their overt counterparts due to their reduced cognitive loads. Experimenter-paced single-word production tasks also pose a similar problem: albeit providing the behavioral correlate, the single-word production tasks are qualitatively different from the word fluency tasks performed within a limited time period, and may produce lower cognitive loads (Abrahams et al., 2003; Basho, Palmer, Rubio, Wulfeck, & Muller, 2007).

Conversely, fNIRS measurement is relatively immune to these problems due to its less straining experimental setting, and thus it possesses substantial potential for applications such as linguistic functional monitoring (reviewed in Dieler, Tupak, and Fallgatter (2012)). In particular, fNIRS enjoys a low susceptibility to movement-related noise that is often entailed in overt verbal fluency tasks. This feature has been most quantitatively demonstrated by Schecklmann, Ehlis, Plichta, and Fallgatter (2010) in their simultaneous fNIRS and EMG measurements over the fronto-temporal areas during an overt word fluency task, revealing fluency-related activation and no systematic association between fNIRS and EMG signals. Indeed, fNIRS has been implemented in letter and category fluency tasks: typically these studies demonstrate bilateral activations in the inferior frontal gyri (IFG), middle frontal gyri (MFG), and, more roughly, in the fronto-temporal regions (Ehlis, Herrmann, Plichta, & Fallgatter, 2007; Herrmann, Walter, Ehlis, & Fallgatter, 2006; Kakimoto et al., 2009; Reif et al., 2011; Richter, Herrmann, Ehlis, Plichta, & Fallgatter, 2007; Schecklmann et al., 2007, 2008, 2010; Suto, Fukuda, Ito, Uehara, & Mikuni, 2004) with activation being left-pronounced and higher in the phonological than in the semantic conditions (Ehlis et al., 2007; Schecklmann et al., 2008). In addition, verbal fluency tasks have been used to explore cortical activation patterns specific to psychiatric patients compared to normal, healthy control subjects (e.g., Herrmann, Ehlis, & Fallgatter, 2003; Matsuo, Kato, Fukuda, & Kato, 2000; Suto et al., 2004; Watanabe et al., 1998).

These bodies of literature have presented accumulating evidence that fNIRS is a promising imaging modality for functional assessment during verbal fluency tasks. This further suggests the importance of describing prototypical cortical activation patterns for verbal fluency tasks in order to establish canonical referential data for future clinical diagnoses. Reflecting this notion, a systematic study employing multichannel fNIRS to cover bilateral language-related cortical regions has reported on a comparison of the cortical activation pattern between letter and category fluency tasks. A German group employing 50 subjects revealed oxy-Hb increase in the fronto-temporal cortices with a general left-lateralization in both tasks. This lateralization was more pronounced in the semantic task (Tupak et al., 2012). This general tendency was also confirmed in the older adults, but with bilaterally reduced activation in the inferior frontal junction (IFJ) and increased activation in the middle-frontal and supramarginal gyri (Heinzel et al., 2013). In addition, a Canadian group, setting IFG as the region of interest, reported bilateral activation during category and letter fluency tasks in younger and older adults with reduced activation in the latter (Kahlaoui et al., 2012).

Although prototypical activation patterns for verbal fluency tasks are being elucidated, we now start to face a fundamental question of linguistic studies: generalizability and specificity in languages. It has been demonstrated that even the same reading tasks performed in different languages could recruit different cortical regions. For example, Italian is orthographically more consistent than English: in a PET study during word and non-word reading tasks, Italian readers exhibited greater activation than English readers in the superior temporal regions, involved in phoneme processing (Paulesu et al., 2000). Differences in the orthographical and phonological structures in languages might also affect cortical activation patterns during word fluency tasks.

Phonologically speaking, while English, German, and Italian are all syllable-based languages, Japanese is mora-based. Scriptically, English, German, and Italian are alphabetical, while Japanese is moraic. The syllable is an important phonological unit in syllable-based languages. It is formed around a vowel (V), and a V can take up a few proceeding and subsequent consonants (C). The most common form of syllable in English is CVC. On the other hand, the principal suprasegmental unit in the Japanese language is the mora (Mattys & Melhorn, 2005; Otake, Hatano, Cutler, & Mehler, 1993). A mora is generally composed of a single V or combination of CV, and generally corresponds to a single Japanese phonetic character (McQueen, Otake, & Cutler, 2001; Otake et al., 1993). Accordingly, morae tend to have fewer Cs and Vs than do syllables. In other words, the number of phonetic segments in a word is larger in morae than in syllables. For example, the English word "system" (sys·tem) consists of two segments, while its Japanese version consists of four segments (si·su·te·mu). Conversely, the English word "system" includes six letters, while its Japanese version includes four morae.

Given these orthographical and phonological differences between alphabet-syllable-based and moraic languages, letter fluency tasks in these languages cannot be considered fully compatible, while category fluency tasks are. In letter fluency tasks, usually a target letter is given as a minimum orthographical unit. In alphabet-syllable-based languages, it is a certain alphabetical letter phonologically representing the first C or V, while in moraic languages, the unit is a certain moraic letter that has a one-to-one correspondence with a particular mora sound. In English, a target letter is selected from 26 letters, whereas in Japanese, the target letter can be selected from among up to 67 characters. Taken together, what is referred to as "letters" in alphabet-syllable-based and moraic languages have different orthographical and phonological characteristics. Therefore, we hereafter designate a Japanese letter fluency task as a "mora/letter fluency task".

Indeed, a behavioral psychiatric study suggested that verbal fluency tasks in Japanese may be functionally different from those in alphabet-syllable-based languages. In patients with schizophrenia speaking alphabet-syllable-based languages, category fluency is more disturbed than phonological fluency. However, Japanese-speaking schizophrenic patients tend to exhibit similar impairment for both verbal fluency tasks (Sumiyoshi et al., 2004). This observation suggests that cortical functions recruited for verbal fluency tasks may be different between moraic languages (e.g., Japanese) and alphabet-syllable-based languages (e.g., English, German, and Italian). If this is the case, canonical activation patterns for verbal fluency tasks obtained from alphabet-syllable-based language speakers may not be appropriate for Japanese speakers.