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Attention to language: Novel MEG paradigm for registering involuntary language processing in the brain

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Previous research indicates that, under explicit instructions to listen to spoken stimuli or in speech-oriented behavioural tasks, the brain's responses to senseless pseudowords are larger than those to meaningful words; the reverse is true in non-attended conditions. These differential responses could be used as a tool to trace linguistic processes in the brain and their interaction with attention. However, as previous studies relied on explicit instructions to attend or ignore the stimuli, a technique for automatic attention modulation (i.e., not dependent on explicit instruction) would be more advantageous, especially when cooperation with instructions may not be guaranteed (e.g., neurological patients, children etc). Here we present a novel paradigm in which the stimulus context automatically draws attention to speech. In a non-attend passive auditory oddball sequence, rare words and pseudowords were presented among frequent non-speech tones of variable frequency and length. The low percentage of spoken stimuli guarantees an involuntary attention switch to them. The speech stimuli, in turn, could be disambiguated as words or pseudowords only in their end, at the last phoneme, after the attention switch would have already occurred. Our results confirmed that this paradigm can indeed be used to induce automatic shifts of attention to spoken input. At ~250 ms after the stimulus onset, a P3a-like neuromagnetic deflection was registered to spoken (but not tone) stimuli indicating an involuntary attention shift. Later, after the word-pseudoword divergence point, we found a larger oddball response to pseudowords than words, best explained by neural processes of lexical search facilitated through increased attention. Furthermore, we demonstrate a breakdown of this orderly pattern of neurocognitive processes as a result of sleep deprivation. The new paradigm may thus be an efficient way to assess language comprehension processes and their dynamic interaction with those of attention allocation. It does it in an automatic and task-free fashion, indicating its potential benefit for assessing uncooperative clinical populations.

1. Introduction

Accurate assessment of patients with cognitive and neurological impairments is often a challenge even to the most experienced clinicians. More specifically, in evaluating language function – whether for the purpose of pre-surgical mapping, to assess a child's development, effects of brain injury or to monitor therapy progress – one has always had to rely on behavioural observation or on a combination of behavioural/verbal responses with some neuropsychological tools (e.g., Baron-Cohen, Hoekstra, Knickmeyer, & Wheelwright, 2006; Benton, 1994; Folstein, Folstein, & McHugh, 1975; Shewan & Kertesz, 1980). This raises the problem of non-cooperative subjects. A brain-damaged individual may not be able to properly respond verbally because of collateral lesion-related deficits. A young child, particularly with a speech deficit, may not be willing or able to cooperate with those assessing his or her condition. A "locked-in" person may be conscious but does not have any means to give signs of this behaviourally due to a complete absence of motor control (Laureys, Owen, & Schiff, 2004; Ragazzoni, Grippo, Tozzi,

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& Zaccara 2000); the range of such situations is wide. Clearly, techniques that could reveal neural correlates of language processing without relying on the individual's overt response would be helpful in a variety of situations.

A great potential for this lies with non-invasive brain imaging techniques that have been developing rapidly in the last two decades. For instance, using functional magnetic resonance imaging (fMRI) that tracks oxygen consumption in body tissues, some studies have been able to see whether or not subjects can *mentally* (but not physically) cooperate with an instruction, giving hope for improved assessment of vegetative state and locked-in patients (for review, see Owen & Coleman, 2008). Still, it is often argued (e.g., Hagoort, 2008) that the slow temporal resolution of fMRI is not well suited to the tracking of fast neural activity related to the highly dynamic process of language processing. Indeed, while the blood-oxygenation level develops over seconds reaching maximum at ∼5–6 s (Henson, Price, Rugg, Turner, & Friston, 2002), linguistic processes operate on the temporal scale of hundreds and even tens of milliseconds (Friederici, 2002; Marslen-Wilson, 1975; Pulvermüller, Shtyrov, & Hauk, 2009). For this reason, fast neurophysiological imaging techniques like electro- or magnetoencephalography (EEG, MEG) have been used extensively in the cognitive neuroscience of language (see e.g., Friederici, 2002). These tools track mass neural activity (rather than blood metabolism) with millisecond precision, even though their spatial resolution is generally inferior to metabolic imaging (Dale & Halgren, 2001).

Still, how could one register the activity of neural networks underlying language function without having to apply linguistic tasks such as lexical decision or semantic judgements that require at least the subjects' focussed attention and frequently involve their active participation? To address language function in cases when no active participation is possible, such tasks are clearly ruled out. To address this, a number of experiments used task-free approaches for tracing language-related neural activity. One of methodologies successfully used in such studies is the so-called passive oddball paradigm, in which the subjects are presented with linguistic contrasts between frequent repetitive stimuli and unexpected rare ones without having to perform an overt task (for reviews, see Pettigrew, Murdoch, Chenery, & Kei, 2004; Pulvermüller & Shtyrov, 2006; Shtyrov & Pulvermüller, 2007b). As no attention or stimulus-related task is required (in fact, the volunteers are distracted from the auditory input), the recorded brain activation is considered to be automatic (Näätänen, Paavilainen, Rinne, & Alho, 2007). Furthermore, because the oddball response is elicited by contrasts between the frequent and rare stimuli, this allows for full control over acoustic factors, as the same acoustic contrasts can be incorporated into linguistically different contexts (Shtyrov & Pulvermüller, 2007b).

Indeed, a series of studies using this approach established it as a sensitive tool to study the neural correlates of linguistic access including a wide range of information types: phonological, lexical, semantic and syntactic (Shtyrov & Pulvermüller, 2007b). These have shown that linguistic processing can be activated in the brain – and, importantly, this activation can be recorded in MEG/EEG – without an explicit task or an instruction to focus on the speech input. This raises the possibility of assessing neural linguistic processes non-invasively in subjects who are unable to carry out an active experimental task.

One such obvious linguistic process, utilised routinely in human communication, is so-called lexical access, i.e., access to information about individual words stored in the mental lexicon (a concept defining the store of words in a person's mind, Aitchison, 2002). Lexical access has often been studied using non-attend auditory oddball presentation. The vast majority of such studies have uniformly shown that long-term memory traces for words can become automatically activated in the brain whenever a given word is presented in the spoken input, even if it is not specifically attended to (Pulvermüller and Shtyrov (2006), Shtyrov and Pulvermüller (2007b)). This activation manifests itself as an enhanced early (100–200 ms) event-related oddball response in EEG and MEG (and as enhanced blood oxygenation signal in fMRI), which surpasses that of a similar pseudoword in amplitude, provided that (1) word and pseudoword stimuli are matched acoustically and phonologically and (2) deviant-standard contrasts in word and pseudoword conditions are identical (Endrass, Mohr, & Pulvermüller, 2004; Korpilahti, Krause, Holopainen, & Lang, 2001; Pulvermüller et al., 2001; Shtyrov & Pulvermüller, 2002; Sittiprapaporn, Chindaduangratn, Tervaniemi, & Khotchabhakdi, 2003; Shtyrov, Pihko, & Pulvermüller, 2005; Shtyrov, Osswald, & Pulvermüller, 2008). Importantly, the relative size of word vs. pseudoword activation is different under attended conditions, where pseudowords produce an enhanced response, usually at a later latency (in the N400 range), at least in the context of word-oriented tasks such as lexical decision (e.g., Friedrich, Eulitz, & Lahiri, 2006). Such a pseudoword-driven enhancement of the N400, often seen in a wider, sentential context (e.g., Federmeier, Segal, Lombrozo, & Kutas, 2000), can be taken as a sign of increased processing load caused by the futile search for an non-existent match in the mental lexicon, as well as re-analysis and repair of ill-shaped linguistic input (cf. Kutas & Hillyard, 1980; Lau, Phillips, & Poeppel. 2008). This is different from the passive conditions necessary for the oddball response enhancement which is linked to automatic activation of word memory traces. Thus the two responses likely reflect different processing steps: early automatic and late attention-controlled stages in word processing (MacGregor, Pulvermüller, van Casteren, & Shtyrov, 2012; Shtyrov, 2010).

To investigate this divergence more closely, attend and non-attend conditions were compared directly in an oddball presentation using the same word and pseudoword stimuli, while manipulating subjects' attention to the auditory input. This research indicated that, under explicit instructions to listen to spoken stimuli or in a speech-oriented behavioural task, oddball responses to senseless pseudowords are larger than those to meaningful words whereas the reverse – larger word than pseudoword response – is true in non-attend conditions (Garagnani, Shtyrov, & Pulvermüller, 2009; Shtyrov, Kujala, & Pulvermüller, 2010a). Enhanced word activation was interpreted as an automatic activation of long-term memory traces (not present for pseudowords), which can occur automatically in non-attend designs due to the robustness of words' neural representations (Pulvermüller & Shtyrov, 2006; Shtyrov, 2010). At the same time, most psycholinguistic theories also predict activation for lexical neighbours of words and pseudowords (Marslen-Wilson, 1987). This additional activation quickly becomes extinct when there are no attentional resources available, but, in attend conditions, it is allowed to develop, particularly for pseudoword stimuli (for which lexical selection of a single entry – that can suppress neighbouring traces – cannot be achieved), leading to an increased brain response (Shtyrov, 2010). In addition to electrophysiological investigations, this proposal received clear support and mechanistic explanation from a neurobiologically-based computational model of word memory traces and attention processes in the brain (Garagnani, Wennekers, & Pulvermüller, 2008).

In sum, these differential responses can be interpreted as reflecting activation of word-specific memory traces that is enhanced or suppressed depending on attention allocation to stimulus input. They could therefore be used as a tool to trace lexical processes in the brain and their interaction with attention. However, as the previous studies relied on experimental instructions to attend or ignore the stimuli, a technique for automatic attention modulation (not dependent on explicit instruction) is still necessary to forego the need for an explicit active task, if subjects that are less able to follow such a task are to be tested. Such a technique is proposed and tested in the current study.