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Novel sounds as a psychophysiological measure of listening effort in older listeners with and without hearing loss

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HIGHLIGHTS

- Amplitudes of the Novelty P3 and a late positive potential (LPP) increased with increasing task difficulty.
- Subjects with hearing loss had larger LPP amplitudes compared to subjects with normal hearing.
- Task-irrelevant novel sounds can be used as an indirect objective measure of listening effort during various listening tasks.

ABSTRACT

Objective: To investigate whether task-irrelevant novel sounds presented during an auditory task can provide information about the level of listening effort.
Methods: Event-related potentials (ERPs) were recorded for novel sounds presented during two Experiments, a frequency discrimination task and a speech-perception-in-noise (SPIN) test, each with varying degrees of task difficulty (easy, medium, hard). Difficulty was adjusted to the individual frequency discrimination threshold and 50% speech recognition signal-to-noise ratio (SNR), respectively. Older listeners (age range 60–86 years) with either normal hearing for their age or a mild-to-moderate hearing loss participated.
Results: Amplitudes of Novelty P3 and late positive potential (LPP) increased with increasing task difficulty, whereas amplitudes of N1 and N2 decreased. Participants with hearing loss had significantly larger LPP amplitudes in the easy condition of the SPIN test than did normal-hearing listeners. Most correlations between ERP amplitudes and behavioral data were not significant suggesting that listening effort is not a simple equivalent of behavioral performance.
Conclusions: LPP amplitude appeared to be the most sensitive component for capturing listening effort reflecting the arousal level of the listener.
Significance: ERPs to novel sounds could be easily recorded during hearing tests and provide an objective physiological measure of listening effort, thus supplementing behavioral performance data.

1. Introduction

Aging is associated with changes in the peripheral and central auditory system. In addition to the typical peripheral sensorineural hearing loss, slowed processing speed and a reduced capability of selectively attending to a speaker (inhibitory deficit) may require increased perceptual, cognitive and emotional effort to follow a conversation (Baldwin and Ash, 2011; Chao and Knight, 1997; Committee on Hearing B and Biomechanics, 1988; McCoy et al., 2005; McDowd and Filion, 1992; Pichora-Fuller et al., 1995; Tun et al., 2009). There is evidence from both behavioral and physiological studies that older listeners may perform as well as younger listeners, but they differ considerably in the activation patterns obtained with these measures. Functional magnetic resonance imaging (fMRI) studies have shown that in healthy older adults, there is an activation of additional brain areas during listening compared to younger adults. This recruitment is thought to be compensatory in order to maintain performance at the same level as for younger adults (for a review, see Reuter-Lorenz, 2002; Wingfield and Grossman, 2006). Similar results have been described in studies using event-related potentials (ERPs). Bertoli et al. (2005), for example, found pronounced age-related changes in the later cognitive components of the ERPs for a difficult

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discrimination task in the elderly compared to the young subjects indicating different processing strategies. Getzmann and Falkenstein (2011), investigating speech understanding under challenging listening conditions, reported similar differences in the later cognitive components between young and middle-aged listeners. In contrast, in both studies, there was no difference between elderly and young subjects in the performance of the behavioral tasks. These results were interpreted as correlates of more effortful and compensatory processing in the elderly.

Audiometric measures such as pure-tone audiograms and speech audiometry provide hearing thresholds, percent correct speech recognition scores and signal-to-noise ratios (SNRs), but they do not reflect the stress under which the listener produced this performance (Mackersie and Cones, 2011). An objective measure of listening effort supplementing routine audiometric assessments would therefore be highly beneficial. Such measures could help, for example, to evaluate the success of hearing aid provision and to understand why rehabilitation fails in some persons, while others with the same amount and type of hearing loss are successfully provided with hearing aids.

A review of the literature reveals that studies on listening effort have increased dramatically during the last four years. Different methods have been used to quantify the stress or effort caused by hearing loss or difficult listening conditions. These methods comprise behavioral dual-task paradigms (Anderson Gosselin and Gagné, 2010, 2011; Desjardins and Doherty, 2013; Fraser et al., 2010; Hornsby, 2013; Howard et al., 2010; Picou et al., 2013; Ronnberg et al., 2011; Sarampalis et al., 2009), pupillometry (Engelhardt et al., 2010; Kuchinsky et al., 2013; Zekveld et al., 2010, 2011), eye movement tracking (Ben-David et al., 2011), and galvanic skin response and electromyographic activity (Mackersie and Cones, 2011). In particular, psychophysiological measures may capture the stress related to a difficult listening situation. This stress activates the autonomic nervous system leading to increased arousal and the orienting response.

Surprisingly, auditory ERPs have not been explicitly used to estimate listening effort, although this method with its high temporal resolution would be well suited to elucidate the complex processes underlying hearing and speech comprehension. Listening effort may be considered as a special form of perceptual and/or mental work load. A number of ERP studies have investigated mental and perceptual load using dual-task paradigms. They are based on the concept that processing capacities of the brain are limited (Kahneman, 1973). While participants performed a primary task of interest with varying degrees of difficulty (e.g., visual tracking task), ERPs to a secondary task (e.g., counting infrequently presented auditory stimuli) were recorded. The P3 amplitudes to the auditory stimuli were found to decrease with increasing task difficulty, indicating that more attentional resources had to be allocated to the primary task, while processing of the secondary task was attenuated (Isreal et al., 1980; Kramer et al., 1995; Wickens et al., 1983, 1984).

A major drawback of dual-task paradigms is the reciprocal relationship between the two tasks. The addition of a secondary task may also change performance in the primary task, thus compromising the assessment of the task of interest, that is to say, the primary task. In order to avoid these limitations, ERPs could be recorded to task-irrelevant stimuli while participants focus on a single task, such as used in studies using a passive oddball (Harmony et al., 2000; Lv et al., 2010; Muller-Gass et al., 2006; Ullsperger et al., 2001; Zhang et al., 2006), a distraction (Munka and Berti, 2006; SanMiguel et al., 2008) or a single-stimulus paradigm (Allison and Polich, 2008; Miller et al., 2011), where auditory stimuli were task-irrelevant and did not require attention. Again, and consistent with the results from dual-task ERP studies, amplitudes of P3a for the auditory stimuli were reduced as the difficulty of the task increased.

The studies cited thus far used a cross-modal design (visual–auditory). Studies with an uni-modal design (auditory–auditory) have yielded equivocal results with either reduced, unchanged or even increased P3a amplitudes (Berti and Schroger, 2003; Combs and Polich, 2006; Gomes et al., 2007; Katayama and Polich, 1998; Muller-Gass and Schröger, 2007). Muller-Gass and Schröger (2007) argued that channel separation was less distinct in an auditory-alone setup compared to a cross-modal visual–auditory design; therefore, task-irrelevant stimuli may not be as readily ignored.

While most of these studies have used simple pure tones, some studies have also used novel sounds, either as part of an oddball paradigm (Combs and Polich, 2006; Lv et al., 2010; SanMiguel et al., 2008; Ullsperger et al., 2001) or as single stimuli (Miller et al., 2011). Novel sounds are natural environmental sounds, for example animals, human sounds, musical instruments, noise or machine sounds (Fabiani et al., 1996; Friedman et al., 2001). In the Novelty oddball paradigm, they are presented as unexpected task-irrelevant stimuli causing an involuntary shift in attention, that is, an orienting response. They elicit the P3a or Novelty P3 that most likely reflects the evaluative, conscious aspects of the orienting response. Novelty P3 is larger in amplitude than the P3b elicited by the target stimuli, with the amplitude difference being more marked over the frontal scalp (Friedman et al., 2001), and can be reliably obtained with a small number of trials ($n = 30$). Since novel sounds effectively capture attention, they appear to be more appropriate than simple tones for monitoring perceptual and cognitive load (i.e., listening effort).

The Novelty P3 is followed by a positivity that has been named $P3_2$ (Fabiani and Friedman, 1995; Friedman et al., 1993) or late positive potential (LPP) (Miller et al., 2011). In the absence of a common nomenclature for this late positive component, we will refer to it as LPP, as suggested by Miller et al. (2011). They used task-irrelevant auditory novel stimuli in a single-stimulus paradigm during a visual task with different degrees of difficulty. Participants played a video game at two levels of difficulty and in a third condition viewed the game only. The Novelty P3 and LPP amplitudes decreased across all three Experimental conditions in a graded difficulty-dependent manner suggesting that these components may be the most sensitive to changes in task difficulty. While change of P3 amplitude as a function of task difficulty has been previously described, LPP appeared to provide an even more robust index of task load. This late positive component has received little attention in the literature and its functional significance is largely unknown.

Based on the review of ERP studies summarised above, the current study aimed to measure listening effort using auditory ERPs, in particular the components Novelty P3 and LPP of the responses to task-irrelevant novel sounds presented during auditory tests. Two types of Experiment, a classical three-tone Novelty oddball paradigm with a frequency discrimination task and a more realistic speech-perception-in-noise (SPIN) test were used to explore the feasibility of using novel sounds as a measure of listening effort during different auditory tests. For both Experiments, there were three levels of task demand that were adjusted to the individual frequency discrimination threshold and 50% correct speech recognition SNR determined prior to the Experiments. A spatial channel separation within the auditory modality was created by presenting task-relevant auditory stimuli (pure tones or speech) and task-irrelevant novel stimuli through separate channels (left vs. right ear, in front vs. from behind).

It was hypothesised that Novelty P3 and LPP amplitudes would change with changes in task difficulty. The direction of change (increase or decrease) was not predicted. If the spatial separation was sufficient to establish two separate perceptual channels, then