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Neural effects of cognitive control load on auditory selective attention

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ABSTRACT

Whether and how working memory disrupts or alters auditory selective attention is unclear. We compared simultaneous event-related potentials (ERP) and functional magnetic resonance imaging (fMRI) responses associated with task-irrelevant sounds across high and low working memory load in a dichotic-listening paradigm. Participants performed n-back tasks (1-back, 2-back) in one ear (Attend ear) while ignoring task-irrelevant speech sounds in the other ear (Ignore ear). The effects of working memory load on selective attention were observed at 130–210 ms, with higher load resulting in greater irrelevant syllable-related activation in localizer-defined regions in auditory cortex. The interaction between memory load and presence of irrelevant information revealed stronger activations primarily in frontal and parietal areas due to presence of irrelevant information in the higher memory load. Joint independent component analysis of ERP and fMRI data revealed that the ERP component in the N1 time-range is associated with activity in superior temporal gyrus and medial prefrontal cortex. These results demonstrate a dynamic relationship between working memory load and auditory selective attention, in agreement with the load model of attention and the idea of common neural resources for memory and attention.

1. Introduction

In a selective attention task, sensory perceptual processing of task-irrelevant stimuli is determined by ongoing task characteristics. The level of *difficulty* on a goal directed task has long been thought to be a major factor in attentional selectivity (Sabri, Humphries, Binder, & Liebenthal, 2013a). More recently, the load theory of selective attention proposed that the *type* of mental processing imposed by the task, perceptual versus cognitive control, is equally important (Lavie, 2010; Lavie, Hirst, de Fockert, & Viding, 2004). This model makes opposite predictions as to the effects of perceptual load and cognitive load on task-irrelevant information processing. Numerous studies, using behavioral and neuroimaging measures, have shown that indeed greater perceptual demand on a visual task is associated with reduced interference and successful selective attention, whereas higher demand on cognitive control (e.g., working memory, dual task) is associated with increased processing of irrelevant information (de Fockert, 2013; de Fockert, Rees, Frith, & Lavie, 2001; Kelley & Lavie, 2011; Rees, Frith, & Lavie, 1997; Schwartz et al., 2005; Xu, Monterosso, Kober, Balodis, & Potenza, 2011). The effects of perceptual demand and working memory load on sensory processing of task-irrelevant visual distractors were observed as early as primary visual cortex (area V1) (Bahrami, Lavie, & Rees, 2007; Kelley & Lavie, 2011; Schwartz et al., 2005).

This dissociation between perception and cognitive control has been proposed as evidence in support of the view that there are two distinct mechanisms of attention. According to the load theory, a passive perceptual selection mechanism is engaged under situations when perceptual resources are exhausted (high perceptual load) whereas an active mechanism of cognitive control is involved in maintaining current task goals and reducing additional processing of irrelevant information. When a primary task requires cognitive control operations, maintenance of task goals is consequently compromised due to limited executive control resources (Lavie, 2005, 2010; Lavie et al., 2004). A functional magnetic resonance imaging (fMRI) study that compared the effects of both perceptual and working memory load on neural activity to irrelevant information reported that higher perceptual demand (degraded faces) on a face-repetition detection task reduced processing of task-irrelevant simultaneously presented scenes in the parahippocampal place area (Yi, Woodman, Widders, Marois, & Chun, 2004). In contrast to load theory predictions and previous reports, manipulation of memory load in Yi's study revealed similar levels of activation to the irrelevant scenes in both 0-back and 2-back tasks, suggesting a comparable competition between relevant and irrelevant information posed by the presented visual objects. An alternative explanation for the effects of load might involve hierarchical prediction processing models. In this context, differential activation in sensory cortex could be

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attributed to the computation of prediction errors, whereby a greater error is manifested as greater sensory processing of information that was not explained away by top-down predictions (Clark, 2013; Feldman & Friston, 2010; Friston & Kiebel, 2009; Garrido, Kilner, Kiebel, & Friston, 2007; Rao & Ballard, 1999).

Evidence on the neural effects of task demand and task type on processing irrelevant information in the auditory modality are sparse (cf. Alain & Izenberg, 2003). A recent fMRI study systematically manipulated load in a pitch discrimination and a pitch memory n-back task but focused on task effects in auditory cortex to attended *relevant* sounds (Rinne, Koistinen, Salonen, & Alho, 2009). We recently investigated the effects of perceptual load, modulated parametrically in a signal-detection task, on processing of task-irrelevant sounds using simultaneous recording of event-related potentials (ERPs) and fMRI. Consistent with findings in the visual modality, we found an inverse relationship between perceptual load and neural responses to irrelevant speech sounds, with a linear increase in the auditory cortex blood oxygen level dependent (BOLD) response and in the ERPs at 130–230 ms as perceptual demands decreased (Sabri et al., 2013b; cf. Sabri, Liebenthal, Waldron, Medler, & Binder, 2006). In the present study, we seek to expand on the above results and examine the effects of cognitive control load on processing of task-irrelevant sounds, using an auditory n-back task. One ERP study that reported such a manipulation, using a sound sequence-matching task, demonstrated memory effects on attention in a dual-task paradigm in which inhibition of ignored standard sounds was delayed by approximately 50 ms from low to high memory load (Bidet-Caulet, Mikyska, & Knight, 2010). Similar memory load manipulations using functional imaging techniques are lacking, and whether and how working memory disrupts or alters auditory selective attention is unclear.

Evidence on the relationship between selective attention and working memory comes from studies showing a replicable positive correlation on behavioral performance measures between the tasks (Kane and Engle, 2003). In addition, fMRI research reveals an overlap between attention and working memory networks, including intraparietal sulcus (IPS), superior and middle frontal gyri (SFG, MFG), and frontal eye fields (FEFs), supporting the view that the two cognitive functions share neural resources (Awh, Vogel, & Oh, 2006; Corbetta, Kincade, & Shulman, 2002; Cowan, 1998; Kastner & Ungerleider, 2000; Mayer et al., 2007; Zanto, Rubens, Thangavel, & Gazzaley, 2011). The relationship between working memory performance and modulation of visual ERP components (P1, N1) by attention was demonstrated in a recent study, in which low performance trials were characterized by lack of neural suppression of irrelevant information (Zanto & Gazzaley, 2009).

The present study employed a pitch working memory task and a dichotic listening paradigm to investigate the relationship between working memory load and auditory attention, focusing primarily on sensory perceptual processing of task-irrelevant sounds in auditory cortex using simultaneous recordings of ERPs and fMRI. Our results show that higher working memory load is associated with greater neural processing of task-irrelevant sounds in auditory cortex in the N1 time range, demonstrating a negative correlation between memory task demand and selective attention. The results are in agreement with the load model of attention and the idea of common neural resources for memory and attention.

2. Material and methods

2.1. Subjects

Participants were 20 healthy adults (10 men, mean age=25 years, SD=5) with no history of neurological or hearing impairments and normal or corrected-to-normal visual acuity. The participants were native English speakers, and all were right-handed according to the Edinburgh Handedness Inventory (Oldfield, 1971). Data from 7 subjects were excluded from ERP analysis (6 with noisy EEG, 1 due to equipment failure). Informed consent was obtained from each participant prior to the experiment, in accordance with the Medical College of Wisconsin Institutional Review Board.

2.2. Task design and procedure

The study employed a block design and a dichotic listening paradigm. There were eight simultaneous ERP/fMRI dichotic-listening runs, each divided into four blocks of 51 s each. Each block was followed by a 12 s rest period. A block was composed of 17 3 s trials, in which a single 100 ms tone was presented to the Attend ear during the 1.2 s between image acquisitions. Across the trials in each block, tones were 1000, 1790, or 3375-Hz with equal probability. An n-back memory task on the tones was modulated to create two memory load task conditions (NBACK1 and NBACK2). The memory load was fixed within a block. Half of the blocks included task-irrelevant syllables presented to the Ignore ear. In these Syllable blocks, a single syllable (/ba/, /da/, /bi/, /di/, /bu/, /du/, /be/, /de/, /bo/, or /do/, selected randomly without replacement), 180 ms in duration, was presented to the Ignore ear on 10 of the trials. The tone (in the Attend ear) and syllable (in the Ignore ear) were presented such that they did not overlap temporally (ISI=600 ms). Seven trials within the Syllable block did not include a syllable. Trials were pseudo-randomized within each block such that the ISI between successive syllables in the Syllable blocks was jittered exponentially between 3 and 15 s. In the entire experiment, there were 80 syllable trials per task condition. Control blocks were identical except that speech sounds were not presented. Four blocks (2 Syllable and 2 Control for each of the NBACK1 and NBACK2 tasks) were delivered randomly within each run.

Participants performed an n-back matching task in the Attend ear and were instructed to ignore the irrelevant speech sounds presented to the other ear. The task condition, NBACK1 or NBACK2, was conveyed to the participants on the screen immediately before each block. Attend and Ignore ear designation was fixed within a run and varied pseudo-randomly across runs with equal assignment to each ear across the experiment. Participants were instructed to press button 1 for a match and button 2 for a mismatch. A cross-hair was presented in the middle of the screen to assist in minimizing eye movement.

An event-related localizer run, designed to identify areas sensitive to speech stimuli, followed the eight dichotic-listening runs. In the localizer run, participants discriminated between randomly presented 180 ms binaural tones and syllables by pressing buttons 1 and 2, respectively. The syllables were identical to those used in the dichotic-listening runs. Tones were 10 logarithmically spaced sinewaves ranging from 200 to 4000 Hz. Stimulation consisted of 40 syllable and 40 tone events in randomized order, occurring during 1.2 s between image acquisitions. ISI was jittered exponentially between 3 and 9 s.

The syllables were recorded from a male native English speaker and normalized according to loudness. Sounds were delivered through MRI-compatible STAX SR-003 electrostatic ear inserts (STAX, Saitama Prefecture, Japan), which were combined with a Bilsom over-the-ear muff providing approximately 23 dB of passive noise reduction (Bilsom, Sweden). The visual fixation stimulus was projected through an Epson LCD video projector onto an angled mirror located just above the eyes. Stimulus delivery was controlled by a personal computer running Presentation software (Neurobehavioral Systems, Inc. Albany, CA).