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ERP evidence of early cross-modal links between auditory selective attention and visuo-spatial memory

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ABSTRACT

Previous dual-task research pairing complex visual tasks involving non-spatial cognitive processes during dichotic listening have shown effects on the late component (Ndl) of the negative difference selective attention waveform but no effects on the early (Nde) response suggesting that the Ndl, but not the Nde, is affected by non-spatial processing in a dual-task. Thus to further explore the nature of this dissociation and whether the Nd waveform is affected by spatial processing; fourteen adult participants performed auditory dichotic listening in conjunction with visuo-spatial memory in a cross-modal dual-task paradigm. The results showed that the visuo-spatial memory task decreased both the Nde and Ndl waveforms, and also attenuated P300 and increased its latency. This pattern of results suggests that: (1) the Nde reflects a memory trace that is shared with vision when the information is spatial in nature, and (2) P300 latency appears to be influenced by the discriminability of stimuli underlying the Nde and Ndl memory trace.

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1. Introduction

An important question to answer in cognitive neuroscience involves elucidating the nature of the functional relationship between attention and working memory. There is a general agreement that these processes reflect complementary cognitive systems that often operate together to facilitate certain complex behaviour (Cabeza et al., 2003; de Fockert, Rees, Frith, & Lavie, 2001; Engle, 2002; Kane & Engle, 2003; LaBar, Gitelman, Parrish, & Mesulam, 1999). However, the specific interactions between these systems is not fully understood particularly when information is encountered in more than one sensory modality. Since it is known that there are strong links between audition and vision (Driver & Spence, 1998; Eimer & Schroger, 1998), the focus of the present experiment was to further explore the relationship between attention and working memory with event-related potentials (ERPs) in a cross-modal dual-task paradigm that combined auditory selective attention, and visuo-spatial working memory.

When ERPs are recorded during a classic version of the dichotic listening paradigm (Hillyard, Hink, Schwent, & Picton 1973), and the ERP from the unattended stimuli is subtracted from the attended ERP, an endogenous negativity is observed that has two parts: an early negative difference (Nde), and a late negative difference (Ndl). These two components are thought to reflect overlapping, but distinct processes associated with auditory selective attention. Nde appears maximal at frontocentral electrodes, and typically peaks between 70 ms and 200 ms after stimulus onset. Nde has been shown to reflect the processing of simple stimulus features such as pitch (Alho, 1992; Woods, 1990), and evidence suggests that it is generated by a neural source within the auditory cortex (Giard, Perrin, Pernier, & Peronnet, 1988; Rif, Hari, Hamalainen, & Sams, 1991; Woldorff et al., 1993). It has been proposed that Nde reflects a temporary feature recognition system that consists of a series of overlapping memory traces that function to determine the suitability of the incoming stimulus for further processing (Näätänen, 1992). According to this theory, the simple physical characteristics of the stimuli are compared to a representation held in memory that contains the relevant stimulus features. This matching process terminates when the current stimulus is found to differ from the template. Therefore, the closer the feature-match is between the incoming stimulus and the template; the longer the process takes, which leads to a larger amplitude and longer latency of Nde. It has been argued that this comparison process is reflected by a processing negativity (PN), and the Nd represents the manifestation of the difference between the two PNs that reflect relevant stimuli and irrelevant stimuli respectively (Näätänen, 1992). However, it has been suggested that the selection of stimuli for further processing may not entirely depend upon physical characteristics. For instance it has been proposed

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that Nde is sensitive to perceptual context, and that selective processing of the stimuli occurs at different perceptual levels (Alain, Achim, & Richer, 1993; Alain & Arnott, 2000; Alain & Woods, 1994; Arnott & Alain, 2002).

The nature of the information processing mechanisms underlying the frontally distributed Ndl is not as well understood as that of Nde. It has been shown that Ndl peaks in the range 300–600 ms after stimulus onset, and Näätänen, (1992) has suggested that it involves frontal lobe generators. The Ndl is reduced by practice (Shelley et al., 1991; Woods, 1990) and it has been shown to reflect the analysis of multidimensional stimuli (e.g., Woods & Alain, 2001; Woods, Alho, & Algazi, 1994). Teder-Salejarvi and Hillyard (1998) reported that Ndl amplitude was largest in response to stimulus locations adjacent to an attended location in a horizontal array. This indicates that Ndl may reflect the extended processing of stimuli in order to verify their relative spatial locations. Moreover, Ndl is more sensitive than Nde to the magnitude of the physical difference between the attended and unattended stimuli (Hansen & Hillyard, 1980), and it is larger at longer inter-stimulus intervals (Hansen & Hillyard 1984; Näätänen, Gaillard, & Varey 1981). Based on this evidence, Näätänen (1990) suggested that Ndl may represent the "further processing" of the incoming stimulus, as well as selective rehearsal of the to-be-attended stimulus; which he termed "the attentional trace". More recently, the roles of Nde and Ndl during auditory selective attention have been investigated with a series of experiments that employed a dual-task interference paradigm in which a primary visual task was used to probe the Nd components elicited during a secondary dichotic listening task. The dual-task paradigm is a useful tool in attention research because performance costs associated with the introduction of perceptual-cognitive load can be attributed to limitations within the attention system. These limitations have been suggested to reveal either central processing bottlenecks (Pashler, 1984), capacity sharing limitations, or crosstalk interference between specific cognitive processes (Pashler & Johnson, 1998). ERP studies that make use of dual-task paradigms generally rely on the assumption that changes in the latency and amplitude of ERP waveforms under load, compared to single task conditions; reflect the interference effects in the neural processing underlying performance deficits (Gopher & Donchin, 1986). Relying on this logic, the first of these dual-task studies employed a simulated aircraft flying task and showed that, compared to the dichotic task performed alone, the amplitude of Ndl, but not the Nde, was reduced both by the introduction of the flying task, and by an increase in its difficulty (Singhal, Doerfling, & Fowler, 2002). A second finding of interest was that P300 was reduced in concert with the Ndl. The dissociation between the Nde and Ndl was interpreted as indicating that the latter reflects amodal processing rather than unimodal auditory processing because the interference with the auditory Ndl was caused by a visual task. Furthermore, it was suggested that the relationship between Ndl and P300 may be closer than had been previously thought (Singhal et al. 2002). However, due to the complexity of the flying task; the question of which of the various cognitive demands of the flying task was responsible for the reduction of Ndl was left unanswered.

One solution to address this question was to employ simpler visual tasks containing fewer components, thereby allowing more specific inferences to be drawn about the locus and nature of the interference. Accordingly, Singhal and Fowler (2004), Singhal and Fowler (2005) employed both the varied-set (short-term memory, STM) and fixed set (long-term memory, LTM) versions of Sternberg's (1975) visual memory scanning tasks to investigate the cross-modal relationship between Ndl and memory processes. This study showed that Ndl amplitude was reduced by the varied-but not the fixed-set version of the scanning task whereas P300 was sensitive to both, while Nde was unaffected by either version. This pattern of results suggested that Ndl reflects short-term memory processes, but not long-term memory processes, and supported the idea that Nde is a modality specific waveform. Moreover, the suggestion was made that within Baddeley's (1986, 2000) view of working memory (WM); P300 may reflect a general aspect of WM perhaps associated with task difficulty (Kok, 2001), whereas the Ndl may reflect specific processes within the phonological loop (Singhal & Fowler, 2004). Additional support for this position was provided by Ramirez, Bomba, Singhal, and Fowler (2005), who investigated the effects of a modified visual covert attention switching paradigm (e.g. Posner, Nissen, & Ogden, 1978) on the Nd components. This study showed that the valid/invalid condition of Posner's task compared to a neutral control condition, decreased Ndl, but did not affect Nde. Furthermore, P300 dissociated from the Ndl because its amplitude was decreased by both the neutral control and the valid/invalid conditions. It was concluded that Ndl is likely sensitive to attention switching and both Ndl and P300 share sensitivity to an amodal system that is not reflected by Nde. However, since the auditory dichotic listening task to generate the Nd waves employed by Singhal, Fowler and colleagues was primarily a spatial task, the question of whether Ndl is sensitive to *spatial* attentional control, or more general control mechanisms was not answered. Accordingly, Meehan, Singhal, and Fowler (2005) employed a modified version of the Posner task, comparing interference caused by a *spatial* attention switching task with interference caused by a letter matching task (Posner & Mitchell, 1967) so that successive lower- and upper-case letters of the alphabet appeared at the same spatial location, with the former serving as a cue for the latter. The results showed that Ndl was sensitive to interference from the spatial but not the letter matching task suggesting that Ndl reflects *spatial* attentional control, and not deeper non-spatial attentional control mechanisms. Once again, Nde remained unaffected by the experimental manipulations, and when considered with the other previously mentioned dual-task studies; suggests that this component reflects processes that are not compromised by cross-modal dual-task load.

To summarize the dual-task work of Singhal, Fowler and colleagues, Ndl was found to be sensitive to tasks that involve working memory and spatial attention control processes. The pattern of Ndl data dissociated from P300, and importantly for the present study; Nde was found to be insensitive to all of the visual task manipulations. Thus, these studies strongly support Näätänen's (1990) speculation that Ndl involves processing associated with an attentional trace that shares processing resources with other forms of working memory processes. However, these studies also show insensitivity of Nde to the load imposed by the same cognitive tasks, which is not in agreement with Näätänen's (1992) theory that the Nde reflects a self-terminating matching process between incoming stimuli and the representations of to-be-attended stimulus feature retained in a *memory* buffer. However, one other possibility is that Nde does reflect a working memory trace – a *spatial* working memory trace. None of the aforementioned dual-task studies employed spatial memory in the competing tasks, yet the auditory dichotic listening task employed in these studies clearly required a spatial strategy. Thus, we reasoned that it would be important to probe the *spatial* Nd waves with a memory task involving *spatial* information. It has been shown in the literature that an effective way to engage spatial working memory processes is with variations of the visuo-spatial n-back task. An important fact to consider with the n-back task is that it is considered to be more complex than the delayed-response task because the memory demands of the n-back task can be parametrically manipulated while keeping the other task factors relatively constant (McEvoy, Smith, & Gevins, 1998). Indeed, in a large scale meta-analysis study of the n-back task in functional neuroimaging studies, Owen, McMillan, Laird, and Bullmore (2005) showed that

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