



Figure 1 (Scharf). Percentage correct detection of pure tones as a function of their distance in Barks or critical bands from the primary or target frequency whose value is the parameter on the curves.

threshold. Moreover, any such fine modulation in the peripheral system would probably be too small to uncover in the ERP, except perhaps in the very first ones, as measured by the cochleagram. Or perhaps evoked cochlear echoes can serve as a measure; Puel et al. (1988) report that a visual task during auditory stimulation reduced echo amplitude.

In summary, despite the weight of the evidence, I believe it is premature to abandon the possibility that the auditory efferent system mediates conscious efforts to detect (and perhaps also to process) target stimuli by modulating the cochlear response to sound.

Searching for a neurophysiological view of ERP components

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Much of the event-related potential (ERP) work reported in Näätänen's target article seems to fit nicely with possible neurophysiological explanations, as does his corresponding theoretical model. For example, Näätänen claims that mismatch negativity (MMN) is generated by a mechanism responding to the difference between consecutive stimuli, and not to the stimulus per se. In vision, much evidence indicates that a similar automatic differencing mechanism is also at work. In that case, the differencing mechanism operates in space along many different dimensions. In a "preattentive" or simple visual search task, where target and distractors differ on a single dimension (such as orientation, color, or even more abstract dimensions such as closure), the target is said to "pop out" (Julesz & Bergen 1983; Treisman & Gelade 1980). In fact, Kröse (1986) has shown that the greater the difference within a dimension between target and distractor, the easier the discrimination of target from distractors. This is similar to MMN, where the greater the difference between the deviant and standard stimuli, the larger and earlier the MMN.

Neurophysiological evidence for such an automatic mechanism in vision may lie in the center-surround modulation found in cell response. It has been shown that separate populations of

neurons are sensitive to differences in a single feature dimension across a large visual area outside the "classical receptive field" (Allmann et al. 1985; Desimone et al. 1984; Zeki 1983a; 1983b). There is as yet no neurophysiological evidence that a similar center-surround *temporal* modulation mechanism exists in relatively early sensory cortex. Näätänen claims that no MMN appears to occur in the visual modality. However, not finding an MMN in vision (Neville & Lawson 1987) may be the result of not having an equivalent visual paradigm. The differences Näätänen alludes to in the duration of sensory memory for audition and vision may reflect a functional difference of otherwise basically similar structures (i.e., the early modality-specific cortical areas). The fact mentioned by Näätänen that, in congenitally blind patients, the MMN is elicited from visual cortex for auditory stimuli suggests that the neurophysiological mechanism generating the MMN in audition is available in visual tissue.

There also seems to be some neurophysiological evidence of attentional enhancement similar to what Näätänen has suggested generates the N1 effect. For example, Spitzer et al. (1988) trained rhesus monkeys on a visual discrimination task with two levels of difficulty and reported modulation of cell response in area V4 (visual extrastriate cortex) to attended stimuli depending on the amount of attention or "cognitive effort" devoted to such stimuli. They found that when increased effort was required in the more difficult discrimination task, neuronal responses to the oriented or colored stimuli were larger and more selective. A control experiment demonstrated that the heightened neuronal response in the difficult condition was not due to general arousal of all cells in V4 but rather a restricted effect on those cells whose receptive fields contained the attended stimuli. Like the "genuine" N1 enhancement, the modulation of cell response described above reflects a tonically maintained set which is dominant when there are small differences between targets and standards (i.e., difficult discriminations; sect. 5.2). This would seem to support the view that there are two partially overlapping components in the attention effect (Hansen & Hillyard 1980; Näätänen & Michie 1979): an earlier N1 enhancement and a later slow negative shift (PN).

Haenny, Maunsell and Schiller (1988) also report modulation of the responses of neurons in area V4 of the rhesus monkey depending on the behavioral significance of the given visual stimulus. They used a modified matching-to-sample task in which the monkey was required to match the orientation of the cue with the following oriented stimuli. In one task, the monkey was cued tactually by having it feel the orientation of a grooved plate that it could not see, and then tested with visual gratings. Some of the responses of the cells showed a significant interaction between cue and stimulus orientation. For example, a cell that did not respond to either a vertical cue or a vertical stimulus responded when *both* cue and stimulus orientations were vertical. Even though there was no example of a cell selective for all matching conditions (a "match" cell), this study reported that many neurons in V4 responded best to one or more of the matching conditions. Similar results were found when both cue and stimulus were presented visually.

This experiment seems consistent with Näätänen's idea of an "attentional trace" as a maintained representation of the physical features of the relevant stimulus. It occurs relatively early in cortical processing (e.g., V4), in what is traditionally considered sensory-specific cortex (visual cortex). In addition, like the attentional trace, the modulation of cell response by a cue depends on voluntary choice or effort allocation. That is, without attention to the cue (i.e., when the cue does not help in completion of the task), the effects involving orientation-selectivity to the cue stimulus do not occur (Haenny et al. 1988). Some evidence also seems to suggest that this modulation of cell response in V4 is more sensitive to matching than mismatching (cf. sects. 5.5.1, 5.5.5).

It is crucial to pick terms or describe mechanisms in cognitive

science which can eventually be mapped onto the underlying physiology. With such a perspective one may be able to appreciate how, at some level in the brain, there may be little difference, for example, among the representations of a visual stimulus that has been imaged, a visual stimulus which will be the target in a search paradigm, or a visual stimulus which has previously been presented (i.e., the fading representation of an actual stimulus). Within such a context, then, it appears that work in different areas such as imagery, search paradigms (including cross-modal paradigms), and visual perception may have much more in common than is usually assumed. This approach may be especially helpful in the attention literature, with its plethora of terms and paradigms.

Recent work in neurophysiology has described attention at the cell level in many different ways. Many of the mechanisms proposed by Näätänen are compatible with a neurophysiological explanation. However, the definition of a component (sect. 2) should perhaps be more sensitive to underlying neurophysiological constraints. That is, while it is important to try to limit components to localized physiological activity, components, like the ERP waveforms from which they are inferred (via experimental manipulation), can also be composed of multiple cerebral processes. Thus components may consist of activity from several localized physiological areas corresponding to different subcomponents. This is especially clear, for example, when considering a component such as MMN, which can last longer than 100 msec. Within a span of 100 msec, as many as 10 neurons can have fired in sequence, theoretically located in 10 different areas. Nevertheless, given the interconnections between cortical areas (feedforward and feedback pathways) in addition to the possibility that some areas can actually hold the signal (Goldman-Rakic 1987), ERP components probably do to some extent represent localized physiological activity.

On the structure and capacity of selection processes

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The model of auditory information processing developed by Näätänen emphasizes the unique information provided by event-related potentials (ERPs) to the field of auditory selective attention. Näätänen's contribution is particularly impressive because the proposed model not only provides a plausible interpretative framework in which an extensive body of research (based on both physiological and behavioral measures) can be understood but also because a series of testable hypotheses are generated.

The notion central to Näätänen's model is that the N1, mismatch negativity (MMN), and processing negativity (PN) components of the event-related potential (ERP) provide important information about the nature and time-course of auditory input selections during early stages of perceptual analysis. Rather than critiquing the proposed model *per se*, the focus of this commentary will be to elaborate on additional insights relevant to the role of attention in information processing that can be obtained from an analysis of ERP data. More specifically, by focusing on tasks in which attention either is or is not completely allocated to a single input channel, we feel Näätänen ignores a distinct yet important area of concern – namely, situations where attention is divided across multiple input channels and/or tasks.

Models of divided attention can be classified as either capacity-based or structural. Structural models describe performance variability in terms of changes in the number and nature (typically the duration) of processes intervening between the encod-

ing of a stimulus and the production of a response (McClelland 1979; Sternberg 1969). Capacity, on the other hand, is a hypothetical construct often used interchangeably with a number of other terms such as resources, effort, energetics, and attention (Kahneman 1973; Mulder 1979; Wickens 1980:). In this class of models, changes in performance efficiency are often interpreted in terms of the limited nature of processing capacity. Thus, if a number of concurrently performed tasks demand more capacity than is available, performance on one or more of them will decline.

These two classes of models are often considered to be mutually exclusive; however, in practice there are few pure instances of either of them. Instead, information processing can best be described in a multidimensional space that includes vectors for both capacity and structure.

Näätänen's model focuses on the effects of attending or ignoring stimuli at very early stages of processing. Thus, all auditory stimuli are presumed to be processed rapidly and completely upon registration in sensory memory. Subsequent comparison stages then act to detect either differences between the current input and past input (associated with the MMN) or a match between the current input and a template (attentional trace) designating a relevant subjectively defined input (associated with the PN). Finally, among relevant inputs, only target stimuli are associated with large P300 components. The temporal sequence of the processing activities and their ERP manifestations described by Näätänen implies a hierarchically arranged attentional system.

Capacity also plays a role in Näätänen's model, for while the sensory storage and mismatch processing (associated with the MMN) does not require the allocation of capacity, maintenance of the attentional trace responsible for encoding task-relevant features of stimuli (associated with the PN) is likened to a single channel processing bottleneck. We feel that Näätänen does not develop this aspect of his model as completely as the ERP evidence warrants, however.

A large body of research indicates that ERP components are sensitive to capacity limitations at both early and late stages of selection. Several divided attention studies have shown changes in N1 amplitude that are consistent with the predictions generated by limited capacity models. For example, in a study on auditory selective attention, Parasuraman (1978) found that N1 amplitude was systematically related to the number of separate channels subjects were required to monitor. Similar results have been obtained in the visual modality (Kramer et al. 1988; Van Voorhis & Hillyard 1977).

In a subsequent study, Parasuraman (1985) examined divided attention by varying the processing priority of two streams of stimuli (one auditory and one visual) rather than the number of channels to be monitored. In this task, processing demands were manipulated by instructing subjects to maximize their detection performance on either the auditory or the visual task or to treat both tasks as equally important.

The performance data indicated a tradeoff between the tasks as a function of priority. Significantly, the early negativities obtained in the visual (N160) and auditory (N100) tasks showed a reciprocity as a function of priority – the greater the priority of the task, the larger the amplitude of the N1 associated with it. The P3 component of the ERP has also been shown to be sensitive to the allocation of capacity across concurrently performed tasks (Hoffman et al. 1985; Sirevaag et al. 1989; Strayer & Kramer 1990; Wickens et al. 1983). However, whereas the N1 effect was obtained for both targets and nontargets in the attended channel, the P300 effects were obtained only for attended targets.

This pattern of results is consistent with the hierarchically structured levels of selection in Näätänen's model and, in addition, suggests capacity limitations at several levels of attentional selectivity. The amplitude of both the N1 and the P3 components has been shown to be sensitive to the increased