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5 **Abstract**

6 This chapter describes how event-related potential (ERP) components have been used to answer  
 7 questions about attentional processing. In particular, it discusses how attention modulates the flow  
 8 of sensory processing in relatively simple tasks and how it operates at postperceptual levels in more  
 9 complex dual-task paradigms. The chapter focuses primarily on the variety of attention called *selective*  
 10 *attention*, the processes by which the brain selects some sources of inputs for enhanced processing.  
 11 The first section describes how ERPs first became used in the study of attention, highlighting the  
 12 unique ability of ERPs to answer questions that had puzzled attention researchers for decades.  
 13 The second section describes major ERP attention studies in the auditory and visual modalities,  
 14 respectively. The chapter concludes with a discussion of the operation of attention in  
 15 postperceptual systems, such as working memory encoding and response selection.

16 **Keywords:** event-related potentials, auditory attention, visual attention, object-based attention,  
 17 feature-based attention, attentional blink, psychological refractory period

18 The term *attention* has many meanings, but it typi-  
 19 cally refers to a set of processes that control the flow  
 20 of information through the nervous system (see Luck  
 21 & Gold, 2008; Luck & Vecera, 2002). Attention is  
 22 not a cognitive “module” through which information  
 23 flows, but is instead a collection of processes that  
 24 operate by modulating the activity of other systems  
 25 (e.g., perceptual systems, memory systems, response  
 26 systems). Almost all cognitive systems are influenced  
 27 by attention, and those that are not influenced by  
 28 attention are considered interesting boundary cases  
 29 by attention researchers. Consequently, attention  
 30 influences almost all event-related potential (ERP)  
 31 components, and those that are not influenced by  
 32 attention are considered interesting boundary cases  
 33 by ERP-oriented attention researchers. Thus, a sum-  
 34 mary of ERP components that are modulated by  
 35 attention could easily turn into a summary of all  
 36 ERP components.

37 The goal of this chapter is not simply to catalog  
 38 the effects of attention on ERP components; instead,  
 39 we will focus on those ERP components whose  
 40 modulation by attention has provided insight into  
 41 the nature of cognitive processing. In other words,  
 42 we will describe how ERP components have been  
 43 utilized to answer questions about attentional pro-  
 44 cessing that are difficult to answer with behavioral  
 45 data. In particular, this chapter will discuss how  
 46 attention modulates the flow of sensory processing  
 47 in relatively simple tasks and how it operates at post-  
 48 perceptual levels in more complex dual-task para-  
 49 digms. The operation of attention in more complex  
 50 perceptual tasks, such as visual search, is discussed in  
 51 Chapter 12 of this volume.

52 This chapter focuses primarily on the variety of  
 53 attention called *selective attention*, the processes by  
 54 which the brain selects some sources of inputs for  
 55 enhanced processing. Other varieties of attention,

1 such as vigilance and executive control, have been  
2 studied much less extensively with ERPs (with the  
3 exception of error-related negativity studies, which  
4 are reviewed in Chapter 10 of this volume).

5 This chapter is divided into two main sections.  
6 In the first section, we describe how ERPs first  
7 became used in the study of attention, highlighting  
8 the unique ability of ERPs to answer questions that  
9 had puzzled attention researchers for decades. We  
10 also place special emphasis on experimental design  
11 issues that were first raised in studies of auditory  
12 attention but apply generally to the study of atten-  
13 tion in all modalities. Although the focus of this  
14 chapter is on attention, we hope that this first section  
15 will prove useful to researchers interested in applying  
16 ERPs to answer questions in other cognitive domains.  
17 In the second half of the chapter, we describe major  
18 ERP attention studies in the auditory and visual  
19 modalities, respectively. The chapter concludes with  
20 a discussion of the operation of attention in postper-  
21 ceptual systems, such as working memory encoding  
22 and response selection.

## 23 ERP Approaches to the Study 24 of Selective Attention 25 *The Locus of Selection and the Cocktail 26 Party Problem*

27 Event-related potentials were first used to study  
28 mechanisms of attention in the late 1960s and  
29 early 1970s, a period when cognitive psycholo-  
30 gists were vigorously debating the question of  
31 whether attention operates at an early stage or a late  
32 stage (the classic *locus-of-selection* question). Some  
33 researchers argued that the sensory systems are often  
34 overloaded by a multiplicity of inputs, leading to  
35 impaired sensory representations of the environ-  
36 ment, and that attentional mechanisms are used  
37 to limit processing to a subset of the inputs so  
38 that those inputs will be accurately perceived  
39 (e.g., Broadbent, 1958; Treisman, 1964; Treisman &  
40 Geffen, 1967). This is called the *early selection*  
41 hypothesis. Other researchers argued that perceptual  
42 systems could process multiple inputs in parallel  
43 with no interference, whereas memory, decision,  
44 and response systems were highly limited; these  
45 researchers therefore believed that attention is used  
46 solely to modulate these postperceptual processes  
47 (e.g., Deutsch & Deutsch, 1963; Moray, 1959). This  
48 is called the *late selection* hypothesis. Although clever  
49 experimentalists designed numerous behavioral  
50 experiments that answered many questions about  
51 the nature of attentional selection, behavioral reac-  
52 tion time and accuracy measures were unable to

discriminate definitively between early and late 53  
selection mechanisms, because behavior reflects the 54  
combined influence of early and late stages. 55

Unlike behavioral reaction time and accuracy mea- 56  
sures, which (usually) cannot distinguish among the 57  
slowing of different component processes, the tempo- 58  
ral resolution of ERPs can provide a millisecond-by- 59  
millisecond representation of processing as it unfolds 60  
over time. Therefore, by applying ERPs to the study 61  
of attentional selection, researchers have been able 62  
to directly measure the stages of processing that are 63  
influenced by attention. Specifically, if the early selec- 64  
tion hypothesis is correct, then an attended stimulus 65  
should elicit larger sensory ERP components than an 66  
ignored stimulus; if the late selection hypothesis is 67  
correct, then attended and ignored stimuli should 68  
elicit equivalent sensory ERP components and differ 69  
only in terms of later, postperceptual components. 70

Early ERP research on this issue focused primar- 71  
ily on the auditory modality, using an experimental 72  
paradigm that was designed to be analogous to the 73  
*cocktail party* problem. This is the problem of pro- 74  
cessing the sensory information arising from one 75  
source (e.g., the person with whom you are having a 76  
conversation at a cocktail party) in the face of poten- 77  
tially interfering information from other concurrent 78  
sources (e.g., the other simultaneous conversations 79  
at the party). The relevant and irrelevant input 80  
sources are likely to differ in spatial location, pitch, 81  
or both, so it was hypothesized that listeners would 82  
use these cues to select information for further pro- 83  
cessing. That is, location and pitch information 84  
would be used to select the relevant stimuli, and 85  
more subtle features of the selected stimulus could 86  
then be perceived. For example, the location and 87  
pitch of a particular voice could be used to select 88  
that source of stimulation for further processing 89  
that would identify the words being spoken by that 90  
voice. Because this research was originally devel- 91  
oped in the 1950s, when engineering concepts 92  
from telecommunications were being imported into 93  
the nascent field of cognitive psychology, attention 94  
researchers use the term *channel* to describe a source 95  
of information in the environment. Thus, an 96  
observer might attend to one channel (a particular 97  
voice arising from a particular location) and ignore 98  
other channels (other voices at other locations, other 99  
nonvocal sounds, etc.). 100

The experimental analog of this situation, as 101  
developed by Hillyard and his colleagues (Hansen 102  
& Hillyard, 1980; Hillyard et al., 1973; Schwent 103  
et al., 1976a, 1976b; Woods & Hillyard, 1978), is 104  
shown in Figure 11.1. A sequence of brief tones 105

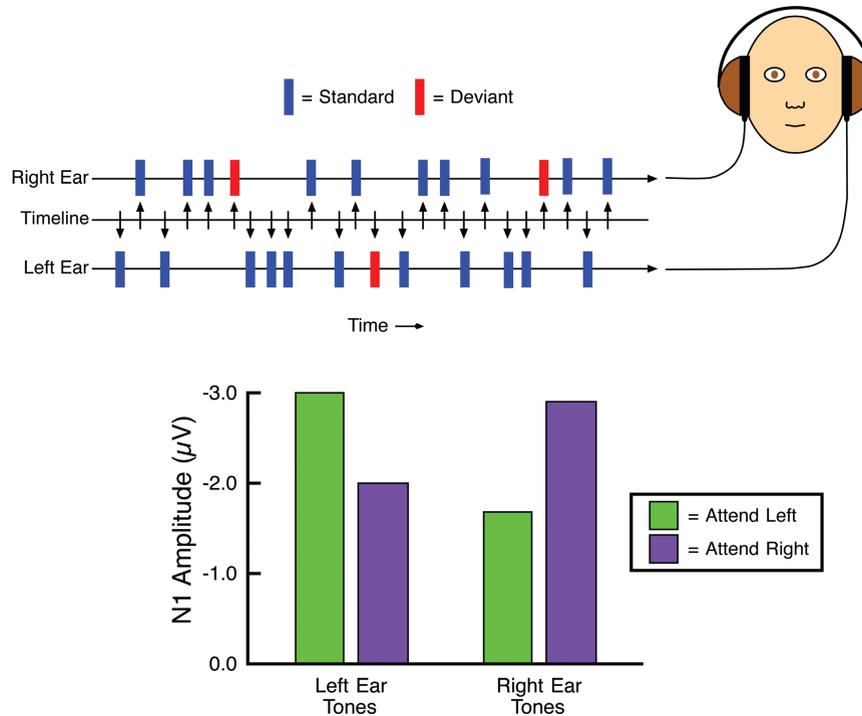


Fig. 11.1. Experimental paradigm and results of Hillyard et al. (1973).

1 is presented, with tones of one pitch presented to  
 2 the left ear and tones of another pitch presented to  
 3 the right ear (thus defining two input channels).  
 4 Subjects are instructed to attend to the stimuli pre-  
 5 sented in one of these channels at the beginning of  
 6 a block of trials and to press a button if they detect  
 7 a slight deviation in this channel (e.g., a slightly  
 8 softer tone presented in the attended pitch/ear com-  
 9 bination). They are further instructed to ignore the  
 10 other channel and not to press the button if a devi-  
 11 ant tone is detected in that ear/pitch combination.  
 12 The goal of this design is to determine the stage at  
 13 which the ERP waveform for an attended stimulus  
 14 differs from the waveform for an unattended stimu-  
 15 lus. An early difference would imply that attention  
 16 operates at an early stage of processing, before per-  
 17 ception is complete, whereas a late difference would  
 18 imply that attention operates only at postperceptual  
 19 stages. Furthermore, it is possible to ask whether  
 20 stimulus deviance is detected by the brain only in  
 21 the attended channel.

22 As shown in Figure 11.1, the N1 wave (ca. 150 ms)  
 23 is typically found to be larger for a given stimulus  
 24 when it is presented in the attended ear than when  
 25 it is presented in the unattended ear (this is true for  
 26 both the standard and deviant stimuli). Because this  
 27 effect began at a relatively early time, during which the

28 brain is presumably engaged in perceptual processing,  
 29 this pattern of results supports early selection theories  
 30 of attention. More precisely, this pattern of results  
 31 has led to the view that attention operates within both  
 32 the auditory and visual modalities as a *sensory gain*  
 33 *control*—like the volume control on a sound system or  
 34 the brightness control on a video monitor—that serves  
 35 to boost the effective intensity of the attended stimuli  
 36 and reduce the effective intensity of the ignored stimu-  
 37 li. Moreover, this gain control can be set prior to the  
 38 presentation of a stimulus, influencing the gain of the  
 39 initial feedforward pass of information through sensory  
 40 cortex (see the review by Hillyard et al., 1998).

### *The Design of Attention Experiments*

41 More details about the results obtained with this  
 42 paradigm will be provided in later sections. First,  
 43 however, we would like to consider some important  
 44 aspects of this experimental design—which we call  
 45 the *Hillyard sustained attention paradigm*—because  
 46 it has been used as the template for an enormous  
 47 number of ERP attention experiments in the audi-  
 48 tory, visual, and somatosensory modalities. There  
 49 are two main issues addressed by this design. First,  
 50 it is important to create a task environment that  
 51 encourages subjects to focus attention appropri-  
 52 ately. Second, it is important to rule out alternative  
 53

1 explanations for differences in the ERP waveforms  
 2 elicited by attended and unattended stimuli. It is  
 3 important to consider these issues very carefully  
 4 when designing an attention experiment or when  
 5 evaluating attention experiments in the literature.

6 **ENCOURAGING A STRONG FOCUS**  
 7 **OF ATTENTION**

8 Because the Hillyard sustained attention paradigm  
 9 was originally developed to determine whether  
 10 attention operates at an early stage of processing,  
 11 experiments using variants of this paradigm are  
 12 typically designed to both facilitate and encourage  
 13 the focusing of attention within perceptual process-  
 14 ing systems. In particular, the stimulus differences  
 15 between the attended and unattended channels are  
 16 large, making it easy to rapidly determine the chan-  
 17 nel to which a given stimulus belongs. In particular,  
 18 if attention operates as a preset gate or gain control,  
 19 then it is necessary to use channels that correspond  
 20 to different pools of neurons at early stages in the  
 21 sensory processing pathway. Otherwise, it would  
 22 not be possible to increase the gain for the neurons  
 23 corresponding to the attended channel prior to  
 24 stimulus onset. In the case of the auditory system,  
 25 tones that differ greatly in pitch stimulate different  
 26 populations of neurons beginning in the cochlea,  
 27 and of course, different pools of neurons code the  
 28 two ears beginning at the cochlea as well. Thus, pre-  
 29 senting stimuli at widely different pitches in sepa-  
 30 rate ears optimizes the opportunity to observe early  
 31 attention effects. If, in contrast, the attended and  
 32 ignored stimuli are not coded by separate pools of  
 33 neurons until a late stage of processing, then atten-  
 34 tion cannot act as a preset gain control at an early  
 35 stage of processing. Indeed, the effects of attention  
 36 at early points in the ERP waveform are abolished  
 37 when the differences between the attended and  
 38 ignored channels are made smaller. For example,  
 39 Hansen and Hillyard (1983) used an attended chan-  
 40 nel defined by a particular pitch and spatial loca-  
 41 tion, and they found that the N1 wave was nearly  
 42 identical for the attended stimuli and for unat-  
 43 tended stimuli that were similar in either pitch or  
 44 spatial location to the attended pitch and location.  
 45 Similar results were obtained in the visual modality  
 46 by Hillyard and Münte (1984), who found that the  
 47 earliest effects of spatial attention were eliminated  
 48 when the attended and unattended locations were  
 49 close together.

50 Whereas the differences between the attended  
 51 and unattended channels are large in this paradigm,  
 52 the differences between the standard and deviant

stimuli within a channel are small. This increases  
 the likelihood that subjects will be motivated to  
 focus attention strongly on the attended channel.  
 If the standard–deviant difference is large, focused  
 attention may not be necessary for the brain to rap-  
 idly discriminate between the standard and deviant  
 stimuli. Indeed, if the standard–deviant difference  
 is large enough, the deviant stimulus may define a  
 distinct sensory channel to which attention can  
 be focused, and the standard stimuli may not fall  
 within this channel, allowing them to be ignored  
 along with the unattended channel. Thus, when  
 the goal is to compare standard stimuli in the  
 attended and ignored channels, it is important to  
 ensure that the standard and deviant stimuli within  
 a channel differ in a manner that cannot easily be  
 discriminated.

It is also important to present the stimuli at a  
 rapid rate (typically, two to four stimuli per second)  
 if the goal is to test the effects of attention on sen-  
 sory processing. A rapid rate is important because it  
 is difficult to focus attention unless the brain faces  
 an overload of stimulation (Lavie, 1995). If the  
 stimuli are presented slowly, then the brain has suf-  
 ficient time to fully process each stimulus, and there  
 would be no reason to selectively perceive the stim-  
 uli in only the attended channel. Indeed, auditory  
 attention has effects at an earlier point in the ERP  
 waveform under higher than lower stimulation rates  
 (Hansen & Hillyard, 1980; Schwent et al., 1976a;  
 Woldorff & Hillyard, 1991).

If these conditions are not met by a given experi-  
 ment, then the absence of effects at an early point in  
 the ERP waveform (e.g., in the N1 latency range)  
 cannot be used as evidence against early selection  
 models of attention in general, but instead indicates  
 the conditions under which early selection occurs  
 (see Vogel et al., 2005, for an extensive discussion of  
 how the locus of selection may vary according to  
 task demands).

93 **AVOIDING CONFOUNDS AND ALTERNATIVE**  
 94 **EXPLANATIONS**

Näätänen (1967) wrote an influential review of early  
 ERP experiments on attention, pointing out  
 a number of shortcomings of many previous experi-  
 mental designs that permitted alternative explana-  
 tions of their results (see also Näätänen, 1975,  
 1992), problems that the Hillyard sustained atten-  
 tion paradigm was designed to rule out. For exam-  
 ple, the most obvious way to manipulate attention  
 would be to have subjects perform an active discrim-  
 ination task on a stream of stimuli in one condition

1 (e.g., pressing one of two buttons, depending on  
 2 the identity of the stimuli) and do some completely  
 3 different task in another condition (e.g., reading a  
 4 book). However, the subject's overall state of arousal  
 5 might differ between these conditions, and this  
 6 could influence sensory processing in a nonselective  
 7 manner, yielding larger ERP responses to all stimuli  
 8 in the active discrimination condition. Thus, to sep-  
 9 arate the effects of selective attention from the effects  
 10 of global arousal, it is important to ensure that  
 11 attentional manipulations influence the relative sensi-  
 12 tivity to attended and unattended channels rather  
 13 than the overall sensitivity of the system to all stimu-  
 14 li. In addition, the ERPs elicited by the stimuli in  
 15 the active discrimination condition would be con-  
 16 taminated by motor potentials that would be absent  
 17 in the other-task condition. It is also important to  
 18 ensure that the experiment does not confound dif-  
 19 ferences in the ERPs elicited by different physical  
 20 stimuli with differences in the ERPs that arise from  
 21 the effects of attention. That is, one cannot compare  
 22 the ERP elicited by one stimulus that is being  
 23 attended (e.g., a 1000 Hz target tone) with the ERP  
 24 elicited by a different stimulus that is being ignored  
 25 (e.g., a 500 Hz nontarget tone), because it will be  
 26 impossible to determine whether any differences in  
 27 the ERPs are a result of attention or a result of the  
 28 physical stimulus properties.

29 The Hillyard sustained attention paradigm  
 30 addresses these potential problems in the following  
 31 manner. Rather than comparing an active discrimi-  
 32 nation condition with a condition in which subjects  
 33 perform a completely different task, this paradigm  
 34 involves comparing two different active discrimina-  
 35 tion conditions that are closely equated for task dif-  
 36 ficulty. In the original version of this task (Hillyard  
 37 et al., 1973), subjects attended to 1500 Hz tone  
 38 pips in the left ear in one condition and attended  
 39 to 800 Hz tone pips in the right ear in the other  
 40 condition; in both conditions, the task was to press  
 41 a button when a slightly higher pitch was detected  
 42 in the attended ear. Thus, a virtually identical task  
 43 was performed in both conditions, which nearly  
 44 perfectly equated overall arousal. In addition, the  
 45 N1 wave for left-ear tones was larger when attention  
 46 was direct to the left ear than when attention was  
 47 directed to the right ear, and the N1 wave for right-  
 48 ear tones was larger when attention was directed to  
 49 the right ear than when attention was directed to  
 50 the left ear. This rules out an explanation in terms  
 51 of overall arousal. If, for example, attending to the  
 52 left ear had been more arousing than attending to  
 53 the right ear, then this should have led to a larger

N1 wave when subjects attended to the left ear 54  
 for both left-ear and right-ear tones, but attending 55  
 to the left ear increased N1 amplitude only for 56  
 left-ear tones. 57

It is not always easy to equate task difficulty in 58  
 this manner. For example, imagine that a researcher 59  
 wanted to examine the effects of attending to speech- 60  
 like stimuli versus attending to pure tones. A single 61  
 stream containing phonemes and pure tones could 62  
 be presented, with subjects being asked to make a 63  
 /ba-/pa/ discrimination on the phonemes in one 64  
 condition and a high-low pitch discrimination on 65  
 the tones in another condition. It would be non- 66  
 trivial to equate the difficulty of these two tasks, and 67  
 subjects might therefore be in a different state of 68  
 arousal in the two tasks. However, arousal-based 69  
 explanations can be ruled out as long as the observed 70  
 attention effects show a complementary pattern in 71  
 which the ERP difference between the attended and 72  
 ignored stimuli are the same for the two tasks. For 73  
 example, if a larger N1 wave is observed for the pho- 74  
 nemes in the attend-phonemes condition than in 75  
 the attend-tones condition and a larger N1 wave is 76  
 observed for the tones in the attend-tones condition 77  
 than in the attend-phonemes condition, the results 78  
 could not be explained by a greater level of overall 79  
 arousal in one of these two conditions. 80

81 The Hillyard sustained attention paradigm also  
 82 rules out a more subtle type of arousal-based expla-  
 83 nation. Imagine that stimuli are presented every  
 84 300–700 ms in the left ear in one sequence, and  
 85 that stimuli are also presented every 300–700 ms in  
 86 the right ear in a completely independent sequence.  
 87 Because the two sequences are independent, there  
 88 are no constraints on the delay between a stimulus  
 89 in one ear and a stimulus in the other ear. However,  
 90 stimuli are always separated by at least 300 ms in a  
 91 given ear. If subjects are asked to detect targets in  
 92 one ear and ignore the other ear, they could poten-  
 93 tially phasically increase their arousal level during  
 94 the period in which a stimulus is expected in the  
 95 attended ear and then decrease their arousal level  
 96 for the 300 ms period during which no stimulus is  
 97 expected in the attended ear. Because stimuli may  
 98 be presented in the unattended ear during this  
 99 300 ms period, the subject could potentially be in  
 100 a decreased state of global arousal when stimuli are  
 101 presented in the unattended ear during this period.  
 102 Thus, any differences in ERP activity between  
 103 attended-ear and unattended-ear stimuli could be  
 104 explained by transient changes in global responsive-  
 105 ness rather than by differences in responsiveness  
 106 between the attended and unattended ears.

1 This problem was solved by Hillyard et al.  
 2 (1973, Experiment 2) by constraining the timing of  
 3 subsequent stimuli irrespective of the ear to which  
 4 the stimuli were presented. That is, a single sequence  
 5 of stimulus times was created (see the timeline in  
 6 Figure 11.1), and each stimulus in this timeline was  
 7 randomly assigned to the left ear or the right ear.  
 8 With this constraint, subjects cannot phasically alter  
 9 their arousal levels in a manner that is different for  
 10 the attended-ear and unattended-ear stimuli. Hillyard  
 11 et al. found the same pattern of N1 attention effects  
 12 in this condition as in a condition in which the stim-  
 13 ulus sequences in the two ears were independent,  
 14 demonstrating that this pattern is not a result of  
 15 phasic changes in arousal. However, almost all subse-  
 16 quent studies have used a single timeline (as in Fig-  
 17 ure 11.1) to ensure that the results are not confounded  
 18 by phasic changes in arousal. An exception to this is  
 19 a recent set of studies using steady-state visual evoked  
 20 potentials (SSVEPs; see Di Russo et al., 2003b;  
 21 Morgan et al., 1996; Müller & Hillyard, 2000;  
 22 Müller et al., 1998), in which the rate of stimulation  
 23 is too fast to permit phasic changes in arousal.

24 Because the stimuli in the Hillyard sustained  
 25 attention paradigm are typically presented at a  
 26 rapid rate, the ERP elicited by stimulus N-1 will  
 27 overlap with the ERP elicited by stimulus N, and  
 28 this will distort the observed waveform for stimu-  
 29 lus N. However, the use of a single timeline guaran-  
 30 tees that the stimuli preceding an attended stimulus  
 31 will be identical (on average) to the stimuli preced-  
 32 ing an unattended stimulus. Consequently, the  
 33 overlapping activity will ordinarily be the same for  
 34 the attended and unattended stimuli. However,  
 35 subtle differences in overlap may remain that can  
 36 confound the comparison between the ERPs elic-  
 37 ited by attended and unattended stimuli (for a  
 38 detailed discussion, see Woldorff, 1993). Moreover,  
 39 if any nonrandom stimulus sequence constraints are  
 40 imposed (e.g., no more than two targets in a row),  
 41 substantial differences in overlapping activity may  
 42 confound the ERPs. Thus, one must be careful to  
 43 consider the effects of overlap in this paradigm.

44 This paradigm is also designed to rule out con-  
 45 tamination from motor-related potentials as an  
 46 explanation for the ERP difference between the  
 47 attended and ignored stimuli. If subjects make a  
 48 response to the attended stimuli and not to the unat-  
 49 tended stimuli, then premotor ERP components will  
 50 be present in the ERP waveform for the attended  
 51 stimuli but not for the unattended stimuli. These  
 52 potentials (e.g., the **Bereitschaftspotential** and the  
 53 lateralized readiness potential) may begin hundreds

of milliseconds before a response, and within 200 ms  
 of stimulus onset (see Chapters 8 and 9, this volume),  
 and so they can contaminate many ERP attention  
 effects. To minimize this contamination, the Hillyard  
 sustained attention paradigm uses frequent standard  
 stimuli and rare deviant stimuli within both the  
 attended and unattended channels and requires a  
 motor response only for the deviant stimuli within  
 the attended channel. The ERPs elicited by the  
 standard stimuli in the attended and unattended  
 channels can then be compared with minimal  
 contamination from motor-related ERP activity.  
 Because the standard and deviant stimuli are quite  
 similar, they fall into the same sensory channel and  
 are therefore subject to the same attention effects, at  
 least at early stages of processing. Indeed, in most  
 cases, the effects of attention at early points in the  
 ERP waveform are the same for the standards and  
 the deviants. It should be noted, however, that sub-  
 threshold motor activity may be elicited by the  
 standards in the attended channel, and so limiting  
 the analyses to the standard stimuli does not com-  
 pletely rule out the possibility of contamination  
 from motor-related ERPs.

**SUMMARY OF EXPERIMENTAL DESIGN**

**CONSIDERATIONS**

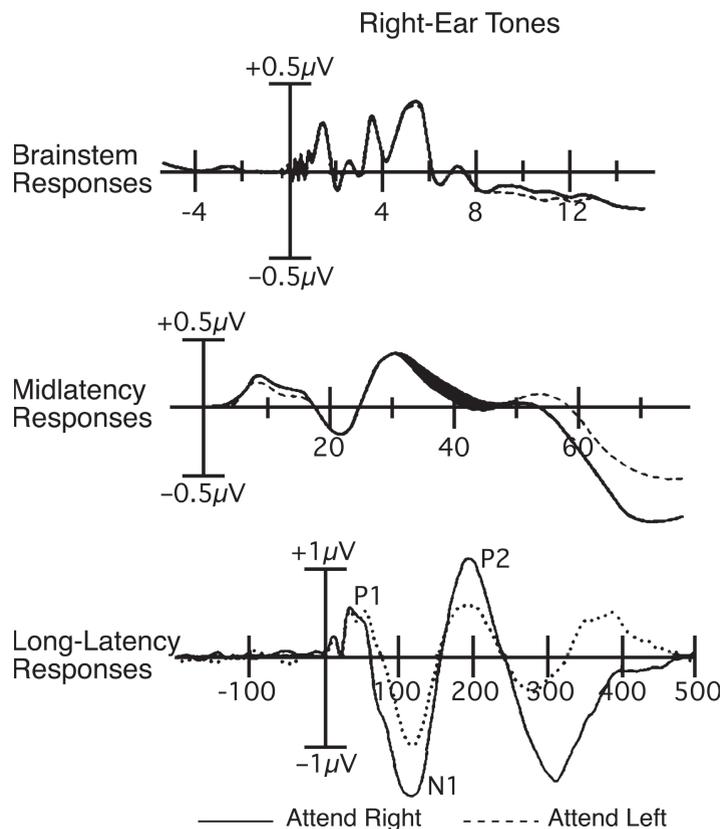
The application of ERPs to the study of selective  
 attention has proved useful in distinguishing among  
 early and late theories of selection mechanisms.  
 However, it is important to note that although ERPs  
 provide a wealth of information regarding the timing  
 of specific cognitive processes, the ERP waveform is  
 highly sensitive to physical and perceptual differ-  
 ences among stimuli (see Luck, 2005, for a full dis-  
 cussion of this issue). Therefore, merely collecting  
 ERPs in conjunction with behavioral measures of  
 attentional selection is not enough to disambiguate  
 alternative explanations of results. Rather, in addi-  
 tion to the many experimental tricks necessary in  
 behavioral experiments of selective attention, such  
 as ensuring a strong focus of attention, ERP atten-  
 tion experiments require additional steps to equate  
 the physical stimulus sequences. The Hillyard sus-  
 tained attention paradigm—which was originally  
 designed for use with auditory attention experi-  
 ments but is easily modified for other modalities—  
 provides an embodiment of these experiment design  
 principles. In the following section, we will see how  
 the use of this paradigm and its many variants has  
 provided a wealth of information about the opera-  
 tion of selective attention in both the auditory and  
 visual modalities.

**AU: Should this term be italicized, as in one of the other chapters.**

1 **Auditory Attention**  
 2 ***Effects of Attention on Auditory Sensory***  
 3 ***ERP Components***

4 As discussed at the beginning of this chapter, the early  
 5 selection hypothesis predicts that sensory ERP compo-  
 6 nents will be enhanced for stimuli presented in the  
 7 attended channel compared to stimuli presented in the  
 8 ignored channel. In addition, this effect should  
 9 be the same for the standard and deviant stimuli,  
 10 because attention is assumed by this hypothesis to  
 11 operate before perception is complete (i.e., before the  
 12 brain has determined whether a given stimulus is  
 13 the target). Some initial studies suggested that the  
 14 brainstem auditory evoked responses that are evoked  
 15 within the first 10 ms following the onset of a stimu-  
 16 lus (see Chapter 4, this volume) could be enhanced  
 17 for attended stimuli (Lukas, 1980, 1981). However, a  
 18 series of studies by Woldorff, Hackley, and Hillyard

(Hackley et al., 1990; Woldorff, 1989; Woldorff  
 et al., 1987) provided convincing evidence that these  
 components are not influenced by attention, even  
 when attention is highly focused. Thus, attention  
 appears to have no influence on the very early trans-  
 mission of auditory information from the cochlea  
 through the brainstem auditory processing nuclei.  
 However, under these highly focused conditions,  
 attention did influence the ERP waveform in the  
 20–50 ms latency range, the time period of the mid-  
 latency responses. This is shown in Figure 11.2, which  
 presents the responses to attended and unattended  
 stimuli on three different time scales, one showing  
 the auditory brainstem responses (0–14 ms), one  
 showing the midlatency responses (0–70 ms), and  
 one showing the longer latency responses (0–500 ms).  
 The first effects of attention are visible in the mid-  
 latency responses. As described in Chapter 4 of



**Fig. 11.2.** Event-related potentials elicited by tones presented to the right ear when the right ear was attended versus when the left ear was attended from the studies of Woldorff et al. (1987) and Woldorff and Hillyard (1991). The same data are shown on three different time scales with different filter settings to focus on the brainstem responses (top), the midlatency responses (middle), and the long latency responses (bottom). The shaded region in the midlatency data shows the earliest effect of attention. Adapted with permission from Woldorff, M., Hansen, J. C., & Hillyard, S. A. (1987). Evidence for effects of selective attention to the midlatency range of the human auditory event related potential. In R. Johnson, J. W. Rohrbaugh & R. Parasuraman (Eds.), *Current Trends in Event-Related Brain Potential Research* (pp. 146–154). London: Elsevier Copyright (1987) and Woldorff and Hillyard (1991).

1 this volume, the auditory midlatency responses are  
 2 thought to arise primarily from auditory cortex, with  
 3 a possible contribution from upper brainstem and  
 4 thalamic nuclei. Thus, auditory attention does appear  
 5 to influence auditory sensory activity by the time  
 6 it reaches cortex, consistent with the early selection  
 7 hypothesis.

8 It is technically demanding to measure the effects  
 9 of auditory attention on ERP activity within the  
 10 first 50 ms following stimulus onset, because these  
 11 early ERP components are small and may be influ-  
 12 enced by attention only when attention is very  
 13 highly focused. The effect of auditory attention that  
 14 was observed first, and most commonly, is therefore  
 15 a later effect in the latency range of the N1 wave  
 16 (ca. 100 ms; see Chapter 4 of this volume for more  
 17 details about the N1 wave). As discussed at the  
 18 beginning of this chapter and illustrated in Fig-  
 19 ure 11.1, Hillyard et al. (1973) reported that the  
 20 amplitude of the N1 wave was greater for a stimulus  
 21 presented in a given ear/pitch combination when  
 22 attention was directed to that ear/pitch combina-  
 23 tion compared to when attention was directed to  
 24 the other ear/pitch combination (see the waveforms  
 25 from a similar study in Figure 11.2). Because the  
 26 N1 wave is a sensory response, Hillyard et al. con-  
 27 cluded that attention operates during perception,  
 28 consistent with the early selection hypothesis.

29 In addition, the N1 effect was the same for both  
 30 the standard and deviant stimuli, indicating that  
 31 it represents selective processing of the attended  
 32 channel before the brain has determined whether the  
 33 stimulus is a standard or a deviant stimulus. If atten-  
 34 tion operates only after stimulus identification is  
 35 complete, as proposed by late selection theories, then  
 36 only target stimuli should benefit from attention,  
 37 and the attended-channel standards should elicit the  
 38 same ERP response as the unattended-channel stan-  
 39 dards. Instead, the initial effects of attention did not  
 40 distinguish between target and nontarget stimuli,  
 41 supporting early selection theories. Moreover, later  
 42 components, such as the P3 wave, were observed for  
 43 the deviants but not for the standards in the attended  
 44 channel, indicating that these components reflect  
 45 processes that follow the classification of a stimulus  
 46 as a standard or a deviant. Moreover, deviant stimuli  
 47 in the unattended channel do not elicit a P3 wave,  
 48 providing evidence for a suppression of perceptual  
 49 processing within the unattended channel (but see  
 50 the following section on the mismatch negativity for  
 51 a more nuanced view).

52 Although Hillyard et al. (1973) clearly demon-  
 53 strated that attention could have an impact in the

54 N1 latency range, Näätänen (1975) proposed that  
 55 this effect was not actually a modulation of the *exog-*  
 56 *enous* (stimulus-evoked) N1 wave. He noted that  
 57 the effect of attention lasted considerably longer  
 58 than the N1 wave (once appropriate filter settings  
 59 were used), and from this observation he concluded  
 60 that the effect of attention consisted of the addition  
 61 of an *endogenous* (internally triggered) component,  
 62 which he called the *processing negativity*. That is,  
 63 he concluded that this endogenous negativity overl-  
 64 lapped with the N1 wave for attended stimuli, arti-  
 65 ficially creating the appearance of a larger N1  
 66 component for the attended stimuli. As discussed  
 67 in Chapter 1 of this volume, arguments based on  
 68 differences in waveshape are weak, because the  
 69 apparent duration (and scalp distribution) of a given  
 70 observed peak depends a great deal on the nature of  
 71 the overlapping components (see also Luck, 2005,  
 72 chap. 2). For example, a long and broad underlying  
 73 N1 component may appear to have a sharp and  
 74 early peak if it is followed by a large and early P2  
 75 wave, but an attention-related modulation of the  
 76 N1 component would have the long and broad time  
 77 course of the underlying N1 component rather than  
 78 showing a sharp and early peak (assuming that it is  
 79 not cut off by a P2 attention effect). Thus, the find-  
 80 ing that the effect of attention extends over a broader  
 81 time range than the observed N1 peak does not nec-  
 82 essarily indicate that the effect of attention reflects  
 83 the addition of a new component.

84 Hansen and Hillyard (1980) replicated the find-  
 85 ing of a sustained difference between the ERPs elic-  
 86 ited by attended versus ignored stimuli, and they  
 87 termed this difference the *Nd* wave (for *negative dif-*  
 88 *ference* wave). However, they also provided evidence  
 89 that the early portion of the attention effect did  
 90 indeed consist of a modulation of the amplitude of  
 91 the exogenous N1 wave. This was supported by a  
 92 magnetoencephalographic study showing that the  
 93 N1 wave and the early portion of the attention effect  
 94 both arise from the same brain region (Woldorff  
 95 et al., 1993). However, the late part of the attention  
 96 effect does appear to reflect a different neural pro-  
 97 cess, as originally proposed by Näätänen (1975).

98 The term *processing negativity*, introduced by  
 99 Näätänen (1975) to describe the difference in ERPs  
 100 to attended versus unattended stimuli in the Hillyard  
 101 sustained attention paradigm, is often used to refer to  
 102 a more negative ERP for stimuli that contain attended  
 103 features, and is used for both auditory and visual  
 104 stimuli. Positive-going effects of this nature can also  
 105 be observed (processing positivities; see, e.g., Anllo-  
 106 Vento & Hillyard, 1996; Anllo-Vento et al., 1998).

1 The polarity of an ERP effect depends on several  
 2 factors, including the location and orientation of  
 3 the generator source and the choice of reference site  
 4 (see Luck, 2005, chap.1), so not all negative-going  
 5 effects necessarily reflect the same kind of neurocog-  
 6 nitive process, and positive-going effects do not  
 7 necessarily reflect fundamentally different kinds of  
 8 processes than negative-going effects. Thus, the terms  
 9 *processing negativity* and *processing positivity* should be  
 10 taken as gross descriptions of experimental effects  
 11 rather than as referring to distinct ERP components  
 12 or distinct neural processes.

### 13 *Effects of Attention on the* 14 *Mismatch Negativity*

15 Although research by Hillyard and his collabora-  
 16 tors favored the early selection hypothesis, evidence  
 17 from the mismatch negativity favored the late selec-  
 18 tion hypothesis. As described in detail in Chapter 6  
 19 of this volume, the mismatch negativity is a nega-  
 20 tive-going deflection peaking approximately 200 ms  
 21 poststimulus that is observed when the eliciting  
 22 stimulus differs from a set of preceding stimuli. In  
 23 the classic oddball paradigm, for example, infre-  
 24 quent tones of one pitch might be interspersed with  
 25 frequent tones of another pitch, and the infrequent  
 26 tones will elicit a mismatch negativity (Näätänen  
 27 et al., 1982). If subjects are actively discriminating  
 28 the tones, the infrequent stimuli will also elicit an  
 29 N2b component and a P3 component (see Chap-  
 30 ter 7, this volume), but the mismatch negativity can  
 31 be observed even if the subjects are ignoring the  
 32 stimuli and engaging in a different task. The mis-  
 33 match negativity can be observed even when the  
 34 frequent and infrequent stimuli differ in a fairly  
 35 subtle manner (e.g., the syllables “ba” versus “ga”).  
 36 Thus, the mismatch negativity appears to reflect an  
 37 automatic discrimination between stimulus catego-  
 38 ries, which is consistent with the notion that a stim-  
 39 ulus can receive extensive sensory processing even  
 40 when attention is not focused on it, as proposed by  
 41 the late selection hypothesis.

42 How can we explain the finding of no effect of  
 43 attention on the mismatch negativity at 200 ms when  
 44 attention appears to influence sensory responses as  
 45 early as 20–50 ms? There are at least two explanations  
 46 (which are not mutually exclusive). First, attention  
 47 must be very highly focused to observe a modulation  
 48 of the earliest sensory responses, and Woldorff and  
 49 his colleagues (Woldorff et al., 1991, 1998) found  
 50 that the mismatch negativity is indeed suppressed  
 51 for mismatching stimuli in one ear/pitch combina-  
 52 tion when attention is highly focused on a different

ear/pitch combination. This is an example of the 53  
 broad principle that attention operates at an early 54  
 stage only when there is a high level of perceptual 55  
 competition, which requires attention to be highly 56  
 focused (Lavie, 1995; Luck & Hillyard, 1999; Vogel 57  
 et al., 2005). 58

A second explanation is that the mismatch nega- 59  
 tivity is generally elicited by mismatches in relatively 60  
 simple features; semantic deviance, for example, 61  
 does not generate a mismatch. Thus, the presence of 62  
 a mismatch negativity does not mean that the unat- 63  
 tended stimuli were fully identified, but only that 64  
 they were identified to a crude level. In other words, 65  
 the effect of attention on the early components cons- 66  
 sists of only a partial suppression of the unattended 67  
 stimuli, and the partial information from the unat- 68  
 tended channel may be sufficient to detect simple 69  
 mismatches. Nonetheless, the fact that the mismatch 70  
 negativity can be observed even when subjects are 71  
 distracted by reading a book does indicate that a rea- 72  
 sonable level of processing can be carried out for 73  
 auditory stimuli even when attention is not actively 74  
 focused on these stimuli. 75

### 76 *Attention and the Discrimination of* 77 *Auditory Conjunctions*

78 Unlike laboratory settings, the natural auditory 79  
 environment is often quite complex, with multiple 80  
 sources contributing a wide array of sounds that can 81  
 overlap in features such as frequency, pitch, and 82  
 location. Therefore, attending to a particular source 83  
 in a natural auditory scene generally requires the 84  
 processing of multiple simultaneously active features 85  
 of acoustic input to isolate the source that has the 86  
 appropriately matching feature dimensions. In other 87  
 words, we are often looking not for specific features, 88  
 but rather for conjunctions of features. Furthermore, 89  
 different features are processed in separate regions of 90  
 auditory cortex, begging the question of how the 91  
 different features get organized into one auditory 92  
 percept.

93 Researchers have debated whether the identifica- 94  
 tion of an object on the basis of a conjunction of 95  
 features occurs as a multistage process that involves 96  
 sequentially assessing the presence or absence of 97  
 each relevant feature, or whether all features can be 98  
 assessed in a parallel fashion. For example, listeners 99  
 may be able to first judge a source of sound on the 100  
 basis of whether it matches the sound of interest 101  
 on a dimension that is easily assessed before moving 102  
 on to the analysis of a more difficult feature. Alterna- 103  
 tively, the analysis of both simple and difficult fea- 104  
 ture dimensions may occur in parallel. Furthermore,

1 it is possible that the features are processed in paral-  
 2 lel, but the processing of a difficult feature may be  
 3 terminated before it is complete once the brain  
 4 determines that the more easily discriminable fea-  
 5 ture dimension does not contain the desired value.  
 6 Alternatively, all features could be examined exhaus-  
 7 tively before a decision is made about an object as a  
 8 whole.

9 The use of ERPs has helped to resolve some of  
 10 these issues regarding the processing of conjunctions  
 11 of features. In the first of these studies, Hansen and  
 12 Hillyard (1983) tested the predictions of parallel  
 13 and serial models of auditory feature analysis using  
 14 tones that varied orthogonally among dimensions of  
 15 pitch, location, and duration. The attended channel  
 16 was defined by a specified location and pitch, the  
 17 values of which were varied across blocks of trials;  
 18 targets were defined by stimulus duration. The pitch  
 19 and location of a given tone could independently  
 20 match or mismatch the relevant feature value, result-  
 21 ing in four classes of stimuli: (1) pitch match, loca-  
 22 tion match; (2) pitch match, location mismatch;  
 23 (3) pitch mismatch, location match; and (4) pitch  
 24 mismatch, location mismatch. The authors used the  
 25 negative difference wave (Nd) to assess whether each  
 26 stimulus was analyzed exhaustively to determine

27 whether it matched the specified pitch and location  
 28 dimensions, or alternatively, whether a stimulus that  
 29 mismatched on one dimension was disregarded  
 30 from further processing on the other stimulus attri-  
 31 bute. The predictions are illustrated in Figure 11.3.  
 32 If the features are processed in parallel, as illustrated  
 33 in Figure 11.3A, the difference between the match  
 34 and mismatch Nd waves for one feature should be  
 35 the same regardless of whether the stimulus matches  
 36 or mismatches the other stimulus dimension.  
 37 In other words, the difference between the Nd wave  
 38 for stimuli that match and stimuli that mismatch  
 39 the location feature should be the same regardless of  
 40 whether the pitch matches or mismatches the chan-  
 41 nel of interest. This would demonstrate an independ-  
 42 ence of the analysis of the features. Alternatively,  
 43 if easily discriminated features are processed in a  
 44 contingent fashion, the amplitude of the Nd wave  
 45 should be similar for the three classes of stimuli that  
 46 mismatch on either one or both feature dimensions,  
 47 whereas the Nd wave for stimuli matching both  
 48 features should be larger (see Figure 11.3B).

49 Hansen and Hillyard (1983) further tested the  
 50 viability of the contingent processing theory by  
 51 independently varying the ease of discriminability of  
 52 the two feature dimensions in separate groups of

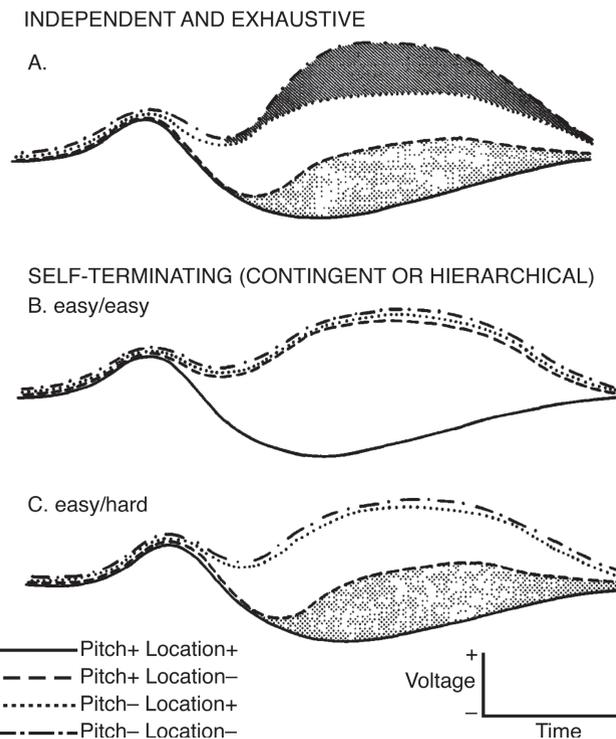


Fig. 11.3. Predicted waveforms from the study of Hansen and Hillyard (1983). Adapted with permission.

1 subjects. Specifically, both easy and hard discrimina-  
 2 tions of pitch and location were employed, such that  
 3 one group of subjects received both easy discrimina-  
 4 tions, a second group received easy pitch and diffi-  
 5 cult location discriminations, and a third group  
 6 received easy location and difficult pitch discrimina-  
 7 tions. For the group with both easy discriminations,  
 8 the contingent processing predictions are as described  
 9 earlier and depicted in Figure 11.3B, in which the  
 10 mismatch of either of the easily discriminated fea-  
 11 tures is similar to the Nd wave for stimuli that mis-  
 12 match on both features. However, as depicted in  
 13 Figure 11.3C, the contingent model predictions  
 14 differ for conjunctions of features if one feature is  
 15 easily discriminated and one feature is more difficult  
 16 to discriminate. In this case, the contingent process-  
 17 ing model predicts that the amplitude of the Nd  
 18 wave will initially reflect whether the more easily dis-  
 19 criminated feature matches the channel of interest,  
 20 with the later part of the Nd wave reflecting whether  
 21 the harder-to-discriminate feature matches the chan-  
 22 nel of interest. For example, if pitch is the more  
 23 easily discriminated feature, the initial part of the  
 24 Nd wave will be similar for pitch match stimuli,  
 25 regardless of whether the location matches the chan-  
 26 nel of interest. However, once the more difficult-to-  
 27 discriminate feature of location is analyzed, the later  
 28 part of the Nd wave will reflect whether the location  
 29 attribute matches or mismatches the channel of  
 30 interest. This provides a further test of the predic-  
 31 tions of the parallel and hierarchical models of con-  
 32 junction feature analysis.

33 The results from all three conditions supported  
 34 a contingent processing theory, in which the pro-  
 35 cessing of one dimension is dependent on the other  
 36 dimension. For example, in the group of subjects  
 37 who encountered both easy pitch and easy location  
 38 discriminations, tones that did not match one of the  
 39 dimensions elicited an ERP that was similar to the  
 40 ERP for tones that mismatched on both dimen-  
 41 sions. Furthermore, for both of the groups with one  
 42 easy and one hard discrimination, the amplitude in  
 43 the later portion of the Nd wave was dependent on  
 44 the negativity elicited by the easily discriminated  
 45 attribute. Specifically, the difficult-to-discriminate  
 46 attribute seemed to be analyzed only if the stimu-  
 47 lus could not be rejected solely on the basis of the  
 48 easily discriminated feature. The authors interpreted  
 49 the pattern of results as being incompatible with  
 50 independent processing of channel attributes and  
 51 compatible with either (1) parallel self-terminating  
 52 models or (2) serial processing models in which the  
 53 easier feature is processed first.

54 Using a similar design, Woods and colleagues  
 55 (1994) further examined the ERP signature of  
 56 conjunction formation by assessing whether the ERP  
 57 to stimuli containing multiple features of interest  
 58 would merely be the sum of ERPs containing each  
 59 of those features individually, or whether an addi-  
 60 tional conjunction-specific ERP signature would be  
 61 present. Furthermore, the authors posited that the  
 62 timing of the ERP components to simple features  
 63 and conjunction-specific ERP signatures would pro-  
 64 vide insight into whether conjunctions were formed  
 65 before or after the individual features were analyzed.

66 The authors examined multiple Nd waves that  
 67 reflected either the ERP activity associated with the  
 68 presence of one individual feature or the ERP activ-  
 69 ity associated with the conjunction of both features  
 70 by using a subtraction procedure, in which the ERP  
 71 to stimuli containing none of the features of inter-  
 72 est was subtracted from the ERP to either individ-  
 73 ual feature only or conjunction stimulus ERPs.  
 74 The authors further examined whether conjunction-  
 75 specific ERP activity was elicited by subtracting both  
 76 of the individual feature Nd waves from the con-  
 77 junction Nd wave to assess the timing of the forma-  
 78 tion of auditory conjunctions. The results indicated  
 79 that initially the individual features were processed  
 80 separately and in parallel, with the conjunction ERP  
 81 activity in the early portion of the waveform equal  
 82 to the sum of the individual feature waveforms.  
 83 However, as processing continued, an additional  
 84 negativity appeared for conjunctions beginning at  
 85 around 120 ms poststimulus. The authors inter-  
 86 preted the relatively early timing of this conjunction-  
 87 specific activity as evidence that auditory conjunctions  
 88 were formed before the individual features were fully  
 89 analyzed.

90 **Effects of Attention on Visual**  
 91 **ERP Components**  
 92 *Overt and Covert Attention in*  
 93 *Visual Perception*

94 Although the general problem of perceiving one  
 95 source of information in the presence of competing  
 96 sources arises in the visual modality just as in the  
 97 auditory and somatosensory modalities, the nature  
 98 of the visual input and visual receptors are very dif-  
 99 ferent, and this leads to some differences in the way  
 100 that attention operates. In the auditory modality,  
 101 stimuli can travel around occluders and around the  
 102 head, and the receptors are exquisitely tuned to  
 103 temporal information but are organized into only  
 104 two physically separable spatial channels (i.e., the  
 105 left and right ears). In contrast, detection of a visual

1 stimulus usually depends on an uninterrupted  
 2 straight line between the stimulus and the receptors,  
 3 and the receptors are spread out over millions of  
 4 individual spatial locations but have relatively poor  
 5 temporal resolution. Moreover, the eyes move con-  
 6 tinually to align the region of highest resolution  
 7 (the fovea) with objects of interest in the environ-  
 8 ment, whereas ear movements (typically resulting  
 9 from head movements) play only a modest role in  
 10 human auditory perception. Most eye movements  
 11 are sudden *saccades*, separated by periods of fixation,  
 12 and vision is suppressed during the saccades. Thus,  
 13 the input to the visual system consists of a series of  
 14 brief snapshots that contain a precise and explicit  
 15 representation of the spatial organization of the  
 16 world. Consequently, an individual who is faced  
 17 with many simultaneous objects can simply look at  
 18 one of the objects to give that object preferential  
 19 access to the fovea, which is the visual system's most  
 20 fundamental processing resource. These shifts of  
 21 gaze are called *overt attention*.

22 This does not mean, however, that the ability to  
 23 make eye movements to an object of interest obvi-  
 24 ates the need for other mechanisms for focusing  
 25 processing resources on objects that are not being  
 26 foveated (for a detailed discussion, see Luck, 2009).  
 27 First, because eye movements are relatively slow, it  
 28 may be useful to facilitate the processing of objects  
 29 at a potentially relevant spatial location prior to  
 30 making an overt shift of gaze, which is called *covert*  
 31 *attention*. These shifts of covert attention may serve  
 32 several different functional roles, including deter-  
 33 mining whether an extrafoveal object is actually  
 34 worth looking at and helping to precisely localize  
 35 the object before the eyes move to it (Luck, 2009).  
 36 Indeed, every saccade appears to be preceded by a  
 37 shift of covert spatial attention (Deubel & Schneider,  
 38 1996; Hoffman & Subramaniam, 1995). Second,  
 39 relevant visual information is often defined by non-  
 40 spatial features (e.g., the color and shape of a pencil  
 41 when one wishes to write something), and it would  
 42 be incredibly inefficient to search for an object by  
 43 moving the eyes randomly from location to location  
 44 until that object is found. Thus, some mechanism  
 45 is necessary to highlight objects that contain task-  
 46 relevant features and are therefore good targets for  
 47 future fixations. Third, once gaze is directed to the  
 48 center of an object, some mechanism is necessary to  
 49 allow perceptual processing mechanisms to expand  
 50 across the extent of the object without also taking  
 51 in other nearby objects. For example, after your  
 52 eyes have been directed to one of the words on this  
 53 page, some mechanism is necessary to allow the

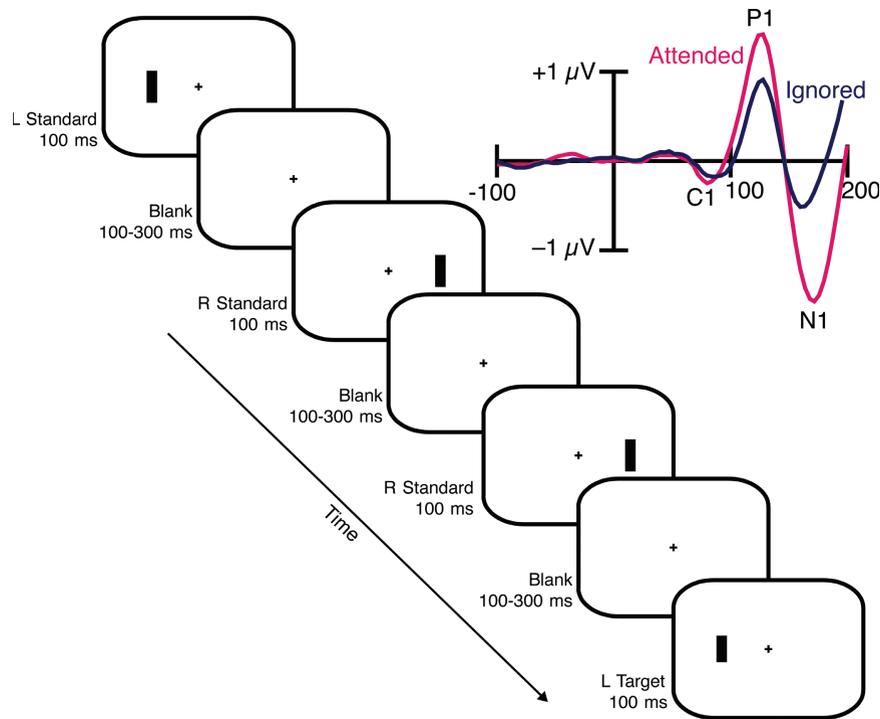
entire word to be processed without interference 54  
 from other words on the lines above and below the 55  
 fixated word. 56

Thus, in addition to overt shifts of gaze, we can 57  
 easily identify at least three other mechanisms of 58  
 attention that are important to the visual system: 59  
 (1) covert spatial attention, which precedes overt 60  
 shifts of gaze; (2) feature-based attention, which 61  
 highlights objects containing relevant features; and 62  
 (3) object-based attention, which allows processing 63  
 to be determined by the shape of the attended 64  
 object. We will now turn to each of these three vari- 65  
 eties of visual attention. However, we would like to 66  
 first note that the experiments and issues examined 67  
 here are largely limited to those that have been 68  
 explored in paradigms in which the attended and 69  
 ignored stimuli are presented at different points in 70  
 time (e.g., variants of the Hillyard sustained atten- 71  
 tion paradigm and the Posner cueing paradigm). 72  
 In natural vision, attended and ignored objects 73  
 are usually visible at the same time. The additional 74  
 issues that arise in this situation will be discussed in 75  
 Chapter 12 of this volume, which focuses on how 76  
 various attentional mechanisms are coordinated in 77  
 the perception of complex multiple-element stimu- 78  
 lus arrays. 79

***Covert Attention to Visual Locations*** 80

The Hillyard sustained attention paradigm has been 81  
 used extensively to study the allocation of attention 82  
 to visual locations. Eason and colleagues (1969) 83  
 published an early study that used this paradigm, 84  
 except that they did not use a single timeline for the 85  
 attended and unattended locations (making it possi- 86  
 ble that the results were a consequence of phasic 87  
 changes in arousal rather than spatially selective pro- 88  
 cessing). Van Voorhis and Hillyard (1977) published 89  
 the first study to implement a fully controlled ERP 90  
 attention paradigm in the visual modality; this was 91  
 followed by a large number of studies that yielded 92  
 similar results (for reviews, see Hillyard et al., 1998; 93  
 Mangun, 1995). 94

A prototypical example of the visuospatial 95  
 variant of this paradigm is shown in Figure 11.4. 96  
 Subjects fixate a central location (and it is absolutely 97  
 crucial that they maintain fixation to avoid con- 98  
 founding changes in processing due to covert atten- 99  
 tion with changes in processing due to differences 100  
 in the positions of the attended and unattended 101  
 stimuli on the retina). At the beginning of each trial 102  
 block, they are instructed to attend either to the left 103  
 visual field (LVF) or to the right visual field (RVF) 104  
 for the duration of that block. A sequence of stimuli 105



**Fig. 11.4.** Typical visual version of the Hillyard sustained attention paradigm, along with data from Gomez Gonzales et al. (1994) showing the results from a variant of this paradigm.

1 is then presented at a rapid rate (two to four stimuli  
 2 per second), with any given item being equally likely  
 3 to appear in the LVF or RVF (i.e., a single timeline  
 4 is used, as illustrated in Figure 11.1). The subjects  
 5 monitor the attended location for occasional deviant  
 6 stimuli, pressing a button when they detect  
 7 these stimuli (and not pressing for deviant stimuli  
 8 presented in the unattended location). Many differ-  
 9 ent types of stimuli have been used as the standard  
 10 and deviant stimuli. For example, the standards and  
 11 targets might be bars of slightly different sizes, dif-  
 12 ferent categories of words, faces with different  
 13 expressions, or just about anything one could imag-  
 14 ine. The main constraint is that, as in the auditory  
 15 version of the paradigm, the target–standard dis-  
 16 tinction must be considerably more difficult to  
 17 discriminate than the differences between the two  
 18 locations, increasing the probability that (1) both  
 19 the standards and deviants fall within the same per-  
 20 ceptual channel and (2) the task is sufficiently dif-  
 21 ficult to motivate subjects to focus attention strongly  
 22 on the to-be-attended location.

### 23 VISUOSPATIAL ATTENTION AND THE C1 WAVE

24 The typical pattern of results is shown in Figure  
 25 11.4 (data from the study of Gomez Gonzales et al.,  
 26 1994). The first component that can be seen in these

27 waveforms is the C1 wave, which arises from area 27  
 28 V1 (Clark et al., 1994; Di Russo et al., 2002; Jeffreys  
 29 & Axford, 1972). Because of the mapping of the  
 30 visual field onto area V1 within the folds of the cal-  
 31 carine fissure, stimuli in the upper and lower visual  
 32 fields project onto areas of V1 with opposite orien-  
 33 tations with respect to the scalp, and this leads to a  
 34 surface-negative voltage for upper field stimuli and  
 35 a surface-positive voltage for lower field stimuli (for  
 36 a detailed discussion, see Clark et al., 1994). When  
 37 the stimuli are presented in the lower field or on the  
 38 horizontal midline, the C1 is difficult to discern  
 39 from the temporally overlapping P1 wave, because  
 40 both are surface-positive voltages and therefore  
 41 merge together. Consequently, a distinct C1 wave is  
 42 not observed in most experiments.

43 When upper-field stimuli are used so that a dis-  
 44 tinct C1 wave can be observed, the C1 wave is not  
 45 typically modulated by visuospatial attention (Clark  
 46 & Hillyard, 1996; Di Russo et al., 2003a; Gomez  
 47 Gonzales et al., 1994; Mangun et al., 1993). This cor-  
 48 responds with a study of single-unit responses in  
 49 macaque monkeys that used a variant of the Hillyard  
 50 sustained attention paradigm and found consistent  
 51 attention effects in area V4, occasional attention  
 52 effects in area V2, and no clear attention effects in area  
 53 V1 (Luck et al., 1997). However, other single-unit

1 studies have found attention effects in area V1  
2 (McAdams & Reid, 2005; Roelfsema et al., 1998)  
3 and even in the lateral geniculate nucleus of the  
4 thalamus (McAlonan et al., 2008). Neuroimaging  
5 studies with human subjects have also found effects  
6 of spatial attention on the blood oxygen-level dependent  
7 (BOLD) response in area V1 (Gandhi et al.,  
8 1999; Somers et al., 1999).

9 To address these discrepancies, Martinez et al.  
10 (1999) used the same subjects and the same attention  
11 task with both functional magnetic resonance  
12 imaging (fMRI) and ERP recordings. They found  
13 no effect of attention on the C1 wave, as in prior  
14 ERP studies, and a significant effect of attention on  
15 V1 BOLD activity, as in prior fMRI studies. One  
16 likely explanation for the pattern of results within  
17 this study and across the previous studies is that  
18 attention does not modulate the first wave of feed-  
19 forward sensory activity in area V1 (as reflected by a  
20 lack of C1 attention effects); however, later feedback  
21 signals sent to area V1 from other areas are modu-  
22 lated by attention (as reflected by the V1 BOLD  
23 attention effects). Indeed, source localization results  
24 in the Martinez et al. study suggested that attention  
25 did have an effect on ERP activity arising from  
26 area V1 later in the ERP waveform (see also Di  
27 Russo et al., 2003a). Moreover, some of the single-  
28 unit attention effects in area V1 clearly arise well  
29 after the initial wave of feedforward activation  
30 (Roelfsema et al., 1998).

31 However, it is possible that attention can  
32 modulate feedforward sensory activity in area V1  
33 under appropriate task conditions, just as attention  
34 modulates auditory ERP responses in the 20–50 ms  
35 latency range only under conditions of highly  
36 focused attention, as discussed earlier in this chap-  
37 ter. One study has found an effect of visuospatial  
38 attention on C1 amplitude (Kelly et al., 2008), sug-  
39 gesting that attention can sometimes influence feed-  
40 forward sensory activity in area V1, but it remains  
41 to be seen whether this result can be replicated.

#### 42 BASIC P1 AND N1 ATTENTION EFFECTS

43 The earliest widely replicated ERP effect of visu-  
44 ospatial attention is a larger P1 wave for stimuli pre-  
45 sented at the attended location than for stimuli  
46 presented at the unattended location, which is usu-  
47 ally accompanied by a larger N1 wave for the stimuli  
48 at the attended location (for reviews, see Hillyard  
49 et al., 1998; Mangun, 1995). These P1 and N1  
50 effects, which are illustrated in Figure 11.4, have  
51 been seen both in the Hillyard sustained attention  
52 paradigm (e.g., Hillyard & Münte, 1984; Mangun

& Hillyard, 1987, 1988) and in the Posner cuing  
53 paradigm (e.g., Eimer, 1994a, 1994b; Hopfinger &  
54 Mangun, 1998; Luck et al., 1994; Mangun &  
55 Hillyard, 1991).  
56

57 In the Posner cuing paradigm, each trial contains  
58 a cue and a target, and the cue indicates the likely  
59 location of the target for that trial and therefore  
60 induces the subject to attend to that location. On  
61 *valid* trials, the target appears at the cued location  
62 (which is presumably also the attended location).  
63 On *invalid* trials, the target appears at an uncued  
64 location. Some experiments also include *neutral*  
65 trials, on which the cue does not provide any infor-  
66 mation about the likely target location. In contrast  
67 to the Hillyard sustained attention paradigm, the  
68 Posner cuing paradigm requires subjects to respond  
69 to the target no matter where it appears. The advan-  
70 tage of this is that behavioral measures of attention  
71 can also be obtained. Specifically, the speed and/or  
72 accuracy of the target detection response are typi-  
73 cally best on valid trials, worst on invalid trials, and  
74 intermediate on neutral trials (although the specific  
75 pattern depends on a variety of factors). The main  
76 disadvantage of the Posner cuing paradigm is that  
77 much more time is required to obtain a given  
78 number of trials in the ERP waveforms, especially  
79 for invalid trials. That is, only a fraction of the tar-  
80 gets are presented at the unattended location (typi-  
81 cally 10%–20%), and the need for a cue, a target,  
82 and a response on each trial leads to a relatively large  
83 amount of time between targets (typically 2–3 s).  
84 This contrasts with the Hillyard sustained attention  
85 paradigm, in which half of the stimuli are presented  
86 at the unattended location and two or three stimuli  
87 are presented per second. It is also possible that  
88 motor-related activity will contaminate the ERPs in  
89 the Posner cuing paradigm, although we now know  
90 enough about motor-related ERPs to distinguish  
91 between motor and sensory ERP responses in most  
92 cases (see Chapters 8 and 9, this volume). Thus, the  
93 choice between these paradigms typically reflects a  
94 balance between the desire to maximize the number  
95 of trials per waveform and the ability to relate the  
96 results to the extensive behavioral literature.<sup>1</sup>

97 In both paradigms, stimuli presented at the  
98 attended location typically elicit larger P1 and N1  
99 waves than stimuli presented at the unattended loca-  
100 tion (i.e., larger for valid targets than for invalid  
101 targets in the Posner cuing paradigm). The P1 wave  
102 and the P1 attention effect both typically begin  
103 70–100 ms after stimulus onset, with a scalp distri-  
104 bution that is maximal over the lateral occipital lobe,  
105 contralateral to the location of the eliciting stimulus.

1 An ipsilateral P1 wave is also observed, onsetting  
 2 10–20 ms after the contralateral P1, and it is also  
 3 typically larger for attended stimuli than for unat-  
 4 tended stimuli. The presence of an ipsilateral response  
 5 suggests that the P1 wave is generated at a relatively  
 6 late stage of the visual pathway, such as the lateral  
 7 occipital complex, where receptive fields are very  
 8 large and include both visual fields. It is unlikely that  
 9 the P1 wave arises from an earlier stage, such as V4,  
 10 where the receptive fields extend no more than 1°  
 11 beyond the vertical meridian. However, V4 cells have  
 12 large *silent suppressive surrounds* that extend far into  
 13 the ipsilateral field (Desimone et al., 1985; Schein  
 14 & Desimone, 1990), and there is some possibility  
 15 that these inhibitory surrounds contribute to the P1  
 16 wave.

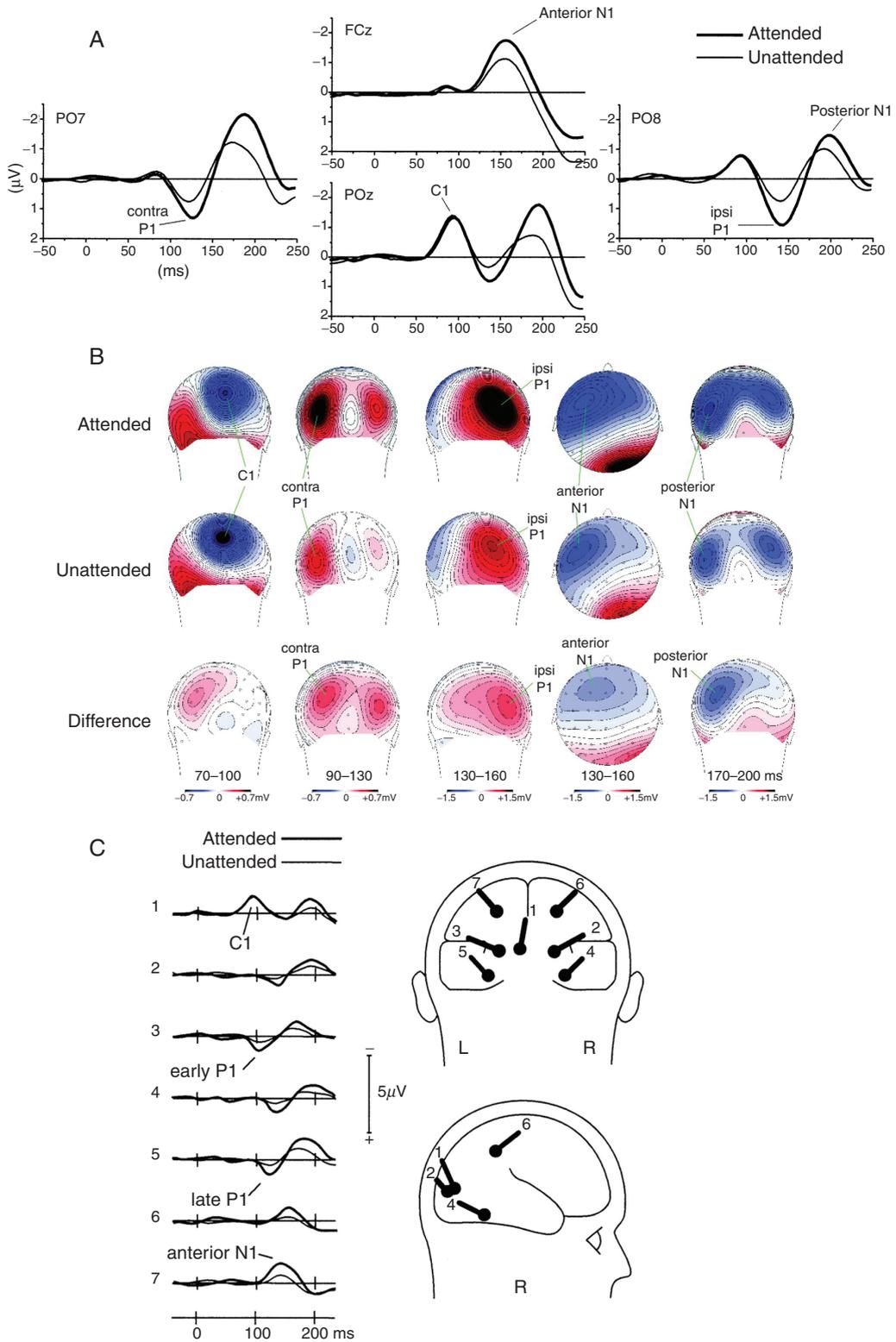
17 Heinze et al. (1994) used a variant of the Hillyard  
 18 sustained attention paradigm with both ERPs and  
 19 positron emission tomography (PET), and they  
 20 found that spatial attention led to both an enlarged  
 21 P1 wave and an increase in blood flow in ventrolat-  
 22 eral occipital cortex. Source localization methods  
 23 indicated that the location of the PET effect was  
 24 consistent with the scalp distribution of the P1  
 25 effect. A similar approach was taken by Di Russo  
 26 and colleagues (2003a), who used fMRI instead of  
 27 PET and presented stimuli in upper and lower loca-  
 28 tions in the LVF and RVF. Subjects monitored one  
 29 of these four locations for target stimuli embedded  
 30 in a stream of standard stimuli (as in the typical  
 31 Hillyard sustained attention paradigm). The wave-  
 32 forms and scalp distributions for upper-right stimuli  
 33 are shown in Figure 11.5. The C1 wave—peaking  
 34 90 ms after stimulus onset with a maximum voltage  
 35 over the occipital pole (electrode POz)—was not  
 36 modulated by whether attention was directed  
 37 toward or away from the location of the stimulus,  
 38 replicating the studies described in the previous sec-  
 39 tion. The P1 wave peaked at approximately 130 ms  
 40 over contralateral occipito-temporal cortex (elec-  
 41 trode PO7) and at approximately 150 ms over the  
 42 ipsilateral hemisphere (electrode PO8), and it was  
 43 larger over both hemispheres when attention was  
 44 directed toward the location of the stimulus. A pos-  
 45 terior N1 wave showed the same pattern but peaked  
 46 approximately 50 ms later over each hemisphere.  
 47 An additional N1 wave was also observed at anterior  
 48 midline sites with a peak latency approximately  
 49 halfway between the P1 and posterior N1 peak  
 50 latencies (approximately 160 ms). This is the most  
 51 common pattern of effects observed in visuospatial  
 52 attention paradigms: a C1 wave over the occipital  
 53 pole that is unaffected by the direction of attention;

P1 and posterior N1 waves over lateral occipitotem- 54  
 poral cortex that are delayed over the ipsilateral 55  
 hemisphere and influenced by the direction of 56  
 attention; and a somewhat earlier and more bilateral 57  
 N1 wave that is observed over fronto-central sites 58  
 and is influenced by the direction of attention. 59

60 When an experimental variable such as the direc-  
 61 tion of attention is shown to increase the voltage in  
 62 the time range of a given ERP component, this does  
 63 not necessarily imply that the experimental effect  
 64 reflects a simple increase in the amplitude of the  
 65 underlying component (see Luck, 2005, chap. 2 and  
 66 Chapter 1, this volume). As discussed previously, for  
 67 example, Näätänen and his colleagues (Näätänen &  
 68 Michie, 1979; Näätänen et al., 1978) argued that  
 69 the auditory N1 attention effect consisted of the  
 70 addition of an endogenous negativity rather than  
 71 a modulation of the exogenous N1 wave (i.e., the  
 72 addition of a process for attended stimuli that was  
 73 not present for unattended stimuli rather than a dif-  
 74 ference in the amplitude of a process that was pres-  
 75 ent for both the attended and unattended stimuli).  
 76 Indeed, subsequent research has shown that this  
 77 proposal was correct for at least part of the N1 atten-  
 78 tion effect (Hansen & Hillyard, 1980). In the visual  
 79 modality, the evidence to date indicates that the P1,  
 80 posterior N1, and anterior N1 attention effects do  
 81 reflect modulations of the exogenous components  
 82 (i.e., modulations of the stimulus-evoked neural  
 83 activity rather than the addition of extra processes  
 84 that are absent for unattended stimuli).

85 The general approach to this issue has been to  
 86 compare the time course and scalp distributions of  
 87 the results for the attended stimuli, the unattended  
 88 stimuli, and the difference between the attended and  
 89 unattended stimuli. The assumption is that, if atten-  
 90 tion operates by simply increasing or decreasing  
 91 the amplitude of the exogenous components, then  
 92 the timing and scalp distribution of the attended  
 93 waveforms will be the same as those of the unat-  
 94 tended waveforms, with only a change in amplitude.  
 95 Moreover, the timing and scalp distribution of the  
 96 attended-minus-unattended difference waveform  
 97 should be the same as those of the unattended wave-  
 98 form. However, this is an oversimplification, because  
 99 it is possible that some components will change  
 100 by more or less than other components, and some  
 101 might not change at all. Under these conditions, it  
 102 is more difficult to compare the time courses and scalp  
 103 distributions directly.

104 Consider, for example, the scalp distributions  
 105 shown in Figure 11.5B. Because the C1 wave over-  
 106 laps in time and space with the P1 wave but C1



**Fig. 11.5.** Data from upper-right stimuli in the study of Di Russo et al. (2003a). (A) Grand average waveforms from selected scalp sites. (B) Scalp distribution of the mean voltage over several time ranges when the stimuli were attended, when the stimuli were unattended, and the difference between attended and unattended. (C) Estimates of the locations and time courses of the internal generator sources. Adapted with permission from Di Russo et al. (2003a).

1 amplitude is not modulated by attention, the differ-  
 2 ence between the scalp distributions of the attended  
 3 and unattended waveforms will reflect only the P1  
 4 wave, whereas the scalp distribution for the unat-  
 5 tended waveform will reflect both the C1 and P1  
 6 waves. Consequently, these scalp distributions look  
 7 very different from each other from 70 to 100 ms,  
 8 and they also look somewhat different from 90 to  
 9 130 ms. Thus, a simple comparison of scalp distri-  
 10 butions or time courses is not enough to determine  
 11 whether an attention effect consists of modulation  
 12 of an exogenous component or the addition of an  
 13 endogenous component.

14 To provide a more detailed analysis, Di Russo  
 15 et al. (2003a) used inverse source localization meth-  
 16 ods to create a model of the neural generator sites of  
 17 the ERP components, using fMRI results from the  
 18 same paradigm to constrain the localization proce-  
 19 dure. The results are summarized in Figure 11.5C,  
 20 which shows the locations of the estimated sources  
 21 and the activation time course for each estimated  
 22 source. Seven dipoles were used to fit the data. The  
 23 C1 wave was represented by a single dipole near stri-  
 24 ate cortex (dipole 1). The other components were  
 25 represented by mirror symmetrical dipole pairs in  
 26 the contralateral and ipsilateral hemispheres, each of  
 27 which was activated 10–20 ms earlier in the contral-  
 28 ateral hemisphere than in the ipsilateral hemisphere.  
 29 The P1 was represented by two dipole pairs, one pair  
 30 in the middle occipital gyrus (dipoles 2 and 3) and  
 31 the other pair more ventrally in the fusiform gyrus  
 32 (dipoles 4 and 5). The posterior N1 was also repre-  
 33 sented by these dipoles; that is, these dipoles showed  
 34 a positive magnitude during the P1 latency range  
 35 and a negative magnitude during the N1 latency  
 36 range.<sup>2</sup> This should not be taken as evidence that the  
 37 P1 and N1 are generated in precisely the same visual  
 38 areas; the spatial resolution of the ERP technique  
 39 may simply be too low to distinguish between the  
 40 P1 and N1 generator sites. Finally, the anterior N1  
 41 wave was represented by a pair of dipoles in the pari-  
 42 etal lobe, near the intraparietal sulcus, that pointed  
 43 anteriorly. Note that the magnitude of the activity  
 44 was greater for attended stimuli than for unattended  
 45 stimuli for each dipole. However, this effect was not  
 46 evident during the initial period of activation for the  
 47 C1 wave; instead, attention appeared to influence  
 48 only later activity coming from this source, consis-  
 49 tent with the hypothesis that attention influences  
 50 only feedback signals in area V1.

51 The model shown in Figure 11.5C was created  
 52 on the basis of the data from the attended and  
 53 unattended waveforms, which are dominated by

stimulus-driven exogenous activity. A second model 54  
 was created on the basis of the attended-minus- 55  
 unattended difference wave, which reflects only the 56  
 changes in activity caused by attention. The loca- 57  
 tions and time courses of this second model were 58  
 very similar to those of the original model. If atten- 59  
 tion led to the addition of endogenous sources with 60  
 distinctly different locations or orientations, then 61  
 the second model should have been substantially 62  
 different from the first model. Thus, the similarity 63  
 of the two models is consistent with the hypothesis 64  
 that attention simply modulates the amplitudes 65  
 of the exogenous ERP components, as would be 66  
 expected if attention operates as a gain control in 67  
 extrastriate visual areas. 68

**NATURE OF THE P1 AND N1 69**  
**ATTENTION EFFECTS 70**

The P1 and N1 waves are obligatory, exogenous 71  
 sensory responses; this is, these waves are present for 72  
 visual stimuli irrespective of top-down factors such 73  
 as intentions, goals, tasks, and so on. These waves 74  
 also vary in amplitude and latency according to low- 75  
 level physical characteristics of the stimuli, such as 76  
 luminance (Johannes et al., 1995). However, these 77  
 voltage deflections represent the sum of several dif- 78  
 ferent underlying components, not all of which may 79  
 be obligatory, exogenous sensory responses. The Di 80  
 Russo et al. (2003) study, for example, found evi- 81  
 dence for two separate attention-sensitive P1 gen- 82  
 erators and three separate attention-sensitive N1 83  
 generators, and similar conclusions were reached by 84  
 Clark and Hillyard (1996). Given that human visual 85  
 cortex contains more than 20 distinct areas, it is 86  
 likely that even more generators contribute to the 87  
 recorded voltage in the P1 and N1 latency ranges 88  
 but cannot be resolved with the ERP technique. 89  
 Thus, although the overall P1 and N1 voltage deflec- 90  
 tions are exogenous, it is not possible to conclude 91  
 that all P1 and N1 subcomponents are exogenous. 92  
 This should be kept in mind when thinking about 93  
 the conclusions that have been drawn about the 94  
 nature of the P1 and N1 attention effects. 95

The simple interpretation of the P1 and N1 atten- 96  
 tion effects is that they reflect a top-down modula- 97  
 tion of the initial feedforward wave of sensory activity 98  
 passing through extrastriate areas of visual cortex (for 99  
 a detailed discussion, see Hillyard et al., 1998). The 100  
 finding that the estimated source waveforms for the 101  
 P1 and N1 sources are larger for attended stimuli 102  
 than for unattended stimuli (as in Figure 11.5C) is 103  
 consistent with this interpretation (although with all 104  
 the caveats that accompany ERP source localization 105

1 models). The P1 and N1 attention effects are also the  
 2 same for target and nontarget stimuli, which is also  
 3 consistent with a simple modulation of feedforward  
 4 sensory activity. That is, if the target were discrimi-  
 5 nated prior to the operation of attention, then one  
 6 would expect the target and nontarget to be differen-  
 7 tially modulated by attention. The current evidence  
 8 is consistent with a simple feedforward gain control  
 9 explanation of the P1 effect, but the posterior N1  
 10 effect may not reflect a simple modulation of sensory  
 11 gain. It is possible to obtain P1 attention effects  
 12 without N1 attention effects and vice versa (e.g., see  
 13 Mangun & Hillyard, 1991; Van Voorhis & Hillyard,  
 14 1977; Vogel & Luck, 2000), and this indicates that  
 15 they do not reflect the operation of a simple gain control  
 16 mechanism that operates prior to the time of the  
 17 P1 wave in a single feedforward processing stream.

18 Luck and his colleagues (Hillyard et al., 1998;  
 19 Luck, 1995, 1998a; Luck et al., 1994; Vogel & Luck,  
 20 2000) have proposed that the pattern of P1 and N1  
 21 dissociations across studies can be explained by the  
 22 proposal that (1) the P1 attention effect reflects a  
 23 suppression of feedforward sensory processing at  
 24 unattended locations to reduce interference in the  
 25 processing of information at the attended location,  
 26 and (2) the N1 attention effect reflects the operation  
 27 of a limited-capacity discrimination process directed  
 28 to the information presented at the attended location.  
 29 This proposal was initially spurred by the spatial  
 30 cuing study illustrated in Figure 11.6. Each trial  
 31 began with either a single cue arrow pointing to  
 32 one of four possible target locations or a set of four  
 33 arrows pointing to all four locations. When a single  
 34 location was cued, the target appeared at that location  
 35 on 75% of trials (*valid* trials) and at one of the  
 36 other locations on 25% of trials (*invalid* trials).  
 37 When all four locations were cued, the target was  
 38 equally likely to appear at any of the locations (*neu-*  
 39 *tral* trials). The P1 wave was reduced in amplitude  
 40 on invalid trials compared to neutral trials, but it  
 41 was not enlarged on valid trials compared to neutral  
 42 trials. That is, compared to the neutral baseline  
 43 condition, focusing attention on the cued location  
 44 led to a suppressed P1 amplitude when the target  
 45 appeared at one of the other locations, but it did not  
 46 lead to an enhanced P1 amplitude when the target  
 47 appeared at the cued location. In contrast, the N1  
 48 wave was enlarged on valid trials compared to neu-  
 49 tral trials, but it was not reduced on invalid trials  
 50 compared to neutral trials. That is, compared to the  
 51 neutral baseline condition, focusing attention on  
 52 the cued location led to an enhanced N1 amplitude  
 53 when the target appeared at the cued location, but it

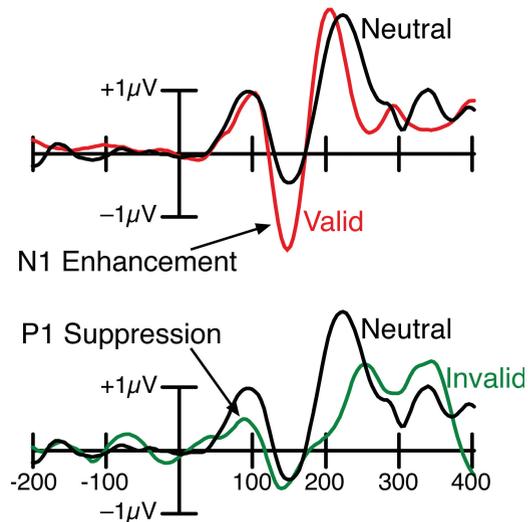
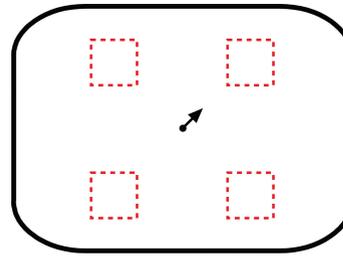


Fig. 11.6. Stimuli and grand average ERP waveforms from the study of Luck et al. (1994). Both rows of ERP waveforms show the ERPs elicited by the target on neutral trials, when attention was directed to all four locations. These neutral waveforms are overlaid by the waveforms elicited by the target when it appeared at the cued location (valid, top row of waveforms) and at the uncued location (invalid, bottom row of waveforms).

54 did not lead to a suppressed N1 amplitude when the  
 55 target appeared at one of the other locations. This  
 56 same pattern of P1 suppression at unattended loca-  
 57 tions and N1 enhancement at attended locations has  
 58 also been observed in the context of a visual search  
 59 paradigm, in which a very different type of neutral  
 60 trial was used (Luck & Hillyard, 1995).

61 Other P1 and N1 dissociations support these  
 62 hypotheses about the P1 and N1 attention effects,  
 63 although somewhat less directly. First, the P1 effect  
 64 is eliminated in visual search tasks when the task  
 65 is changed from conjunction discrimination to feature  
 66 detection (Luck & Hillyard, 1995). It has been pro-  
 67 posed that feature values can be discriminated with-  
 68 out filtering the features of other objects (Luck &  
 69 Ford, 1998; Treisman, 1988), and the lack of a P1  
 70 effect under these conditions supports the hypothe-  
 71 sis that this effect reflects a suppression of potentially

1 interfering features from unattended locations.  
 2 Second, the N1 effect was eliminated in a cuing  
 3 experiment that required a simple target detection  
 4 response, without a discrimination of target identity,  
 5 but it returned when the task was changed to  
 6 require a discrimination of target identity (Mangun  
 7 & Hillyard, 1991). This fits with the hypothesis that  
 8 the N1 effect reflects the operation of a discrimina-  
 9 tion mechanism. Third, the N1 effect but not the P1  
 10 effect is eliminated when items are presented in rapid  
 11 succession at the attended location (Heinze et al.,  
 12 1990; Luck et al., 1990), consistent with the hypoth-  
 13 esis that the N1 effect reflects a mechanism that is  
 14 highly limited in capacity and cannot operate repeat-  
 15 edly in a short period of time.

16 The hypothesis that the N1 wave is related to  
 17 the operation of a limited-capacity discrimination  
 18 mechanism has also been addressed outside the con-  
 19 text of spatial attention experiments. In an early set of  
 20 studies, Ritter and his colleagues (1982, 1983, 1988)  
 21 compared the ERPs elicited by stimuli in two tasks:  
 22 (1) a simple detection task in which subjects simply  
 23 made a speeded response when they detected any  
 24 stimulus and (2) a choice discrimination task in which  
 25 they made different responses, depending on which  
 26 of two stimulus forms was presented. They found that  
 27 the voltage in the N1 latency range was greater in the  
 28 discrimination task than in the detection task, and  
 29 they concluded that this reflects the operation of a  
 30 pattern recognition process. Vogel and Luck (2000)  
 31 replicated this pattern of results and showed that the  
 32 N1 was also larger for a color discrimination task than  
 33 for a simple detection task. They also ruled out several  
 34 confounding factors, such as differences in overlap-  
 35 ping response-related ERP activity and differences  
 36 in arousal. The scalp distribution of this effect was  
 37 comparable to that of the posterior N1 attention  
 38 effect in spatial attention experiments, and they con-  
 39 cluded that both the N1 attention effect and the  
 40 N1 discrimination effect reflect the operation of a  
 41 general-purpose visual discrimination mechanism.  
 42 This mechanism cannot be divided among multiple  
 43 locations; it operates only when attention is allocated  
 44 to a single spatial location. In the Posner cuing pa-  
 45 radigm, therefore, this mechanism is present on valid  
 46 trials (because attention is focused on the location of  
 47 the target), but it is not present on neutral trials  
 48 (because attention is not focused on a single location)  
 49 or on invalid trials (because attention is focused on  
 50 the wrong location). However, it is present in the  
 51 Posner paradigm only when the task involves discrim-  
 52 ination and not simple detection (as observed by  
 53 Mangun & Hillyard, 1991).

**Attention to Nonspatial Visual Features** 54

55 Some theories of visual attention treat location dif-  
 56 ferently from other features (e.g., Moore & Egeth,  
 57 1998; Nissen, 1985; Treisman, 1988; Wolfe, 1994),  
 58 reflecting the fine-grained spatiotopic mapping that  
 59 is present from the very first stages of the visual pro-  
 60 cessing pathway. Other theories, however, do not  
 61 accord any special status to location (e.g., Bundesen,  
 62 1990). Until recently, ERP studies appeared to pro-  
 63 vide strong support for “space-is-special” theories,  
 64 showing that selection based on spatial location  
 65 (*spatial attention*) operates at an earlier stage than  
 66 selection based on nonspatial features (*featural atten-  
 67 tion*). In this section, we will review the typical pat-  
 68 tern of featural attention effects, describe evidence  
 69 that featural attention effects are eliminated when  
 70 stimuli are presented in unattended locations, and  
 71 then present new evidence indicating that featural  
 72 attention can operate at an early stage and independ-  
 73 ently of spatial location under certain conditions.

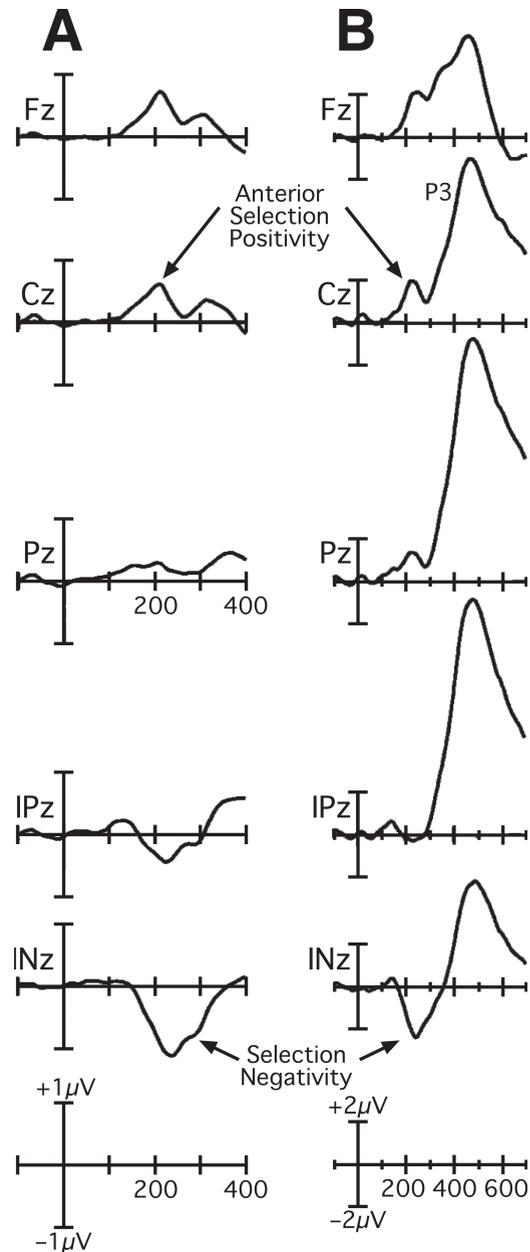
**TYPICAL FEATURAL ATTENTION EFFECTS** 74

75 The Hillyard sustained attention paradigm can be  
 76 easily modified to examine the effects of attending to  
 77 specific orientations, colors, spatial frequencies, and  
 78 other features. As an example, we will consider a  
 79 study of color-based attention in which subjects  
 80 viewed a random sequence of red and blue checker-  
 81 board patterns (Anllo-Vento et al., 1998). Each  
 82 checkerboard was presented for 100 ms, followed by  
 83 a blank interstimulus interval of 50–350 ms. The red  
 84 and blue colors were presented at a standard bright-  
 85 ness for 90% of the checkerboards and at a slightly  
 86 dimmer brightness for the remaining 10%. Subjects  
 87 were instructed to attend either to red or to blue at  
 88 the beginning of a block of stimuli, pressing a button  
 89 when they detected the slightly dimmer deviant  
 90 stimuli in this color and ignoring the standard and  
 91 deviant stimuli in the other color. Each subject  
 92 attended to red for half of the trial blocks and to blue  
 93 for the other half. This made it possible to examine  
 94 the ERPs elicited by a particular color when that  
 95 color was attended versus when that color was  
 96 ignored, thus ruling out any differences in the ERPs  
 97 due to color per se. This is exactly analogous to the  
 98 visuospatial version of the Hillyard sustained atten-  
 99 tion paradigm, but using colors instead of locations  
 100 to define the attended and unattended channels.

101 The results of this study were largely similar  
 102 to those of many other feature-based attention  
 103 studies (Harter & Guido, 1980; Harter & Previc,  
 104 1978; Hillyard & Münte, 1984; Kenemans et al.,  
 105 1993; Previc & Harter, 1982; Wijers et al., 1989).

1 Specifically, when the ERPs were compared for stand-  
 2 dard stimuli presented in the attended and unat-  
 3 tended colors, the ERP waveforms elicited by the  
 4 attended color contained a broad negative-going  
 5 response peaking at around 225 ms at posterior  
 6 scalp sites and a positive-going response peaking at  
 7 around 200 ms at anterior scalp sites. These effects  
 8 are shown as attended-minus-unattended difference  
 9 waves in Figure 11.7A. The broad posterior effect is  
 10 typically termed the *selection negativity*, and the  
 11 more temporally discrete anterior effect is called  
 12 either the *anterior P2 attention effect* or the *anterior*  
 13 *selection positivity*. The same pattern was observed  
 14 for the deviant stimuli, except that the attended-  
 15 color deviant stimuli (i.e., the targets) also elicited  
 16 a large, broadly distributed P3 response (see Fig-  
 17 ure 11.7B). Similar effects are observed when atten-  
 18 tion is directed on the basis of other nonspatial  
 19 dimensions, such as orientation, form, or direction  
 20 of motion, although the scalp distributions may  
 21 vary across dimensions (Anllo-Vento & Hillyard,  
 22 1996). The selection negativity is thought to reflect  
 23 the continued processing of the stimuli containing  
 24 the attended feature value, but little effort has been  
 25 devoted to understanding the anterior selection  
 26 positivity. Related effects can also be observed in  
 27 visual search experiments, in which the ERPs are  
 28 compared for arrays that do or do not contain target  
 29 features (see Chapter 12, this volume).

30 Featural attention does not typically produce the  
 31 same early P1 and N1 effects as spatial attention,<sup>3</sup>  
 32 and some studies have directly examined the rela-  
 33 tionship between spatial and featural attention  
 34 (e.g., Anllo-Vento & Hillyard, 1996; Hillyard &  
 35 Münte, 1984). In the study of Hillyard and Münte  
 36 (1984), for example, subjects attended to stimuli of a  
 37 particular color at a particular location and were  
 38 instructed to detect occasional size deviants among  
 39 the stimuli of the attended color–location combina-  
 40 tion, ignoring size deviants that occurred in the unat-  
 41 tended color and/or location. Thus, the attended  
 42 channel was defined by a combination of color and  
 43 location. Hillyard and Münte observed the typical  
 44 P1 and N1 effects when comparing attended- and  
 45 unattended-location stimuli, and these effects were  
 46 the same whether the stimuli were presented in the  
 47 attended color or the ignored color. They also  
 48 observed the typical selection negativity and selec-  
 49 tion positivity effects when comparing attended- and  
 50 unattended-color stimuli, but only for stimuli pre-  
 51 sented at the attended location. The ERPs did not  
 52 differ between the attended and unattended colors  
 53 for stimuli presented at the unattended location.



**Fig. 11.7.** Grand average difference waves (attended color minus unattended color) for standards (A) and deviants (B) in the study of Anllo-Vento et al. (1998).

From this result, they concluded that featural atten- 54  
 tion is not only later than spatial attention but is also 55  
 contingent on spatial attention. That is, feature-based 56  
 attention mechanisms are applied only to stimuli 57  
 that pass through the initial spatial filter stage. 58

This proposal fits well with space-is-special theo- 59  
 ries of attention based on behavioral data (Moore & 60  
 Egeth, 1998; Nissen, 1985; Treisman, 1988; Wolfe, 61  
 1994), and it makes a fundamental claim about the 62

1 nature of visual attention. However, recent research  
 2 suggests that featural attention can, under certain  
 3 conditions, operate as early as spatial attention and  
 4 independently of spatial attention. In particular,  
 5 featural attention can influence the P1 wave under  
 6 conditions that maximize competition between the  
 7 attended and unattended feature values (Valdes-  
 8 Sosa et al., 1998; Zhang & Luck, 2009).

9 According to the biased competition theory of  
 10 attention (Desimone & Duncan, 1995), attention  
 11 operates primarily to resolve competition between  
 12 concurrent sources of stimuli. Both spatial attention  
 13 effects and featural attention effects are larger when  
 14 attended and unattended stimuli simultaneously  
 15 compete for access to perceptual processing resources  
 16 (Luck et al., 1997; Saenz et al., 2003). In addition,  
 17 single-unit and fMRI experiments using simultane-  
 18 ously visible attended and ignored feature values  
 19 have found featural attention effects in extrastriate  
 20 visual cortex (Saenz et al., 2002; Treue & Maunsell,  
 21 1999). However, ERP studies of featural attention  
 22 using the Hillyard sustained attention paradigm have  
 23 presented the attended and ignored feature values  
 24 sequentially rather than simultaneously, creating  
 25 minimal competition. This may account for the lack  
 26 of early featural attention effects in these studies.  
 27 However, two ERP studies have used experimental  
 28 designs in which attended and ignored colors were  
 29 simultaneously visible, creating strong competition  
 30 between the two colors, and both have reported  
 31 color-based P1 attention effects (Valdes-Sosa et al.,  
 32 1998; Zhang & Luck, 2009).

33 In the study of Valdes-Sosa et al. (1998), subjects  
 34 viewed a cluster of red dots and a cluster of green  
 35 dots that were spatially intermixed (see Figure 11.8).  
 36 The red dots rotated in one direction and the green  
 37 dots simultaneously rotated in the opposite direc-  
 38 tion, giving rise to the perception of two transparent  
 39 overlapping surfaces. Subjects attended either to the

40 red dots or to the green dots. Because the red and  
 41 green dots were randomly distributed across the same  
 42 region of space, the two colors were in strong compe-  
 43 tition with each other. The motion was present for an  
 44 entire trial, and occasional deviation in the motion of  
 45 either the red dots or the green dots was used to elicit  
 46 an ERP. When the deviation occurred in the attended  
 47 color, a larger P1 was elicited than when the devia-  
 48 tion occurred in the unattended color. This was the  
 49 first clear evidence that featural attention could influ-  
 50 ence P1 amplitude under conditions of simultaneous  
 51 competition.

52 A subsequent study demonstrated that color-based  
 53 attention could influence P1 amplitude even when  
 54 the stimuli were presented in an unattended spatial  
 55 location (Zhang & Luck, 2009). As in the Valdes-  
 56 Sosa study, subjects were presented with interdig-  
 57 itated sets of red and green dots (see Figure 11.9).  
 58 Each dot lasted for only a few video frames and was  
 59 then replaced by a dot at a different location. This  
 60 continued for an entire trial, leading to the perception  
 61 of two sets of scintillating dots within the same region.  
 62 Subjects attended either to red or to green dots and  
 63 were instructed to look for occasional dimming of the  
 64 dots in the attended color. The stream of interdig-  
 65 itated red and green dots was presented on one side of  
 66 fixation, and unattended “probe” stimuli were flashed  
 67 occasionally at an unattended location on the other  
 68 side of fixation. These probe stimuli were sets of all-  
 69 red or all-green dots, and they were used to assess the  
 70 processing of the attended and ignored colors outside  
 71 of the attended region. The P1 wave elicited by these  
 72 probes was larger when the color of the probe matched  
 73 the attended color than when it matched the unat-  
 74 tended color. Thus, not only can featural attention  
 75 operate as early as spatial attention, it can also operate  
 76 at unattended spatial locations. To demonstrate that  
 77 these effects were a consequence of the competition  
 78 between the attended and ignored feature values,

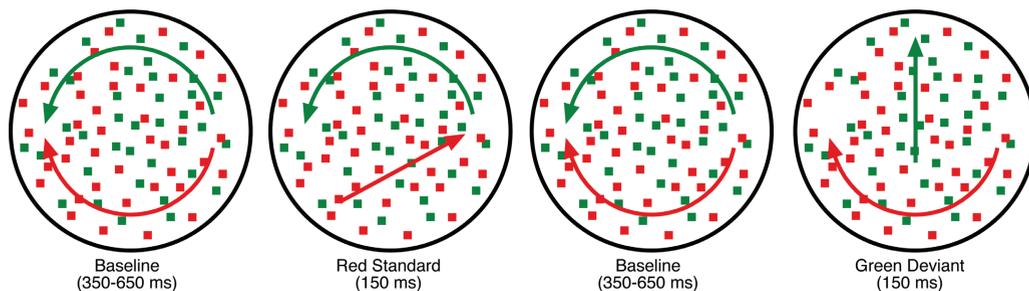


Fig. 11.8. Example sequence of stimuli from the study of Valdes-Sosa et al. (1998). The arrows show the direction of motion of the dots of the corresponding color and were not visible.

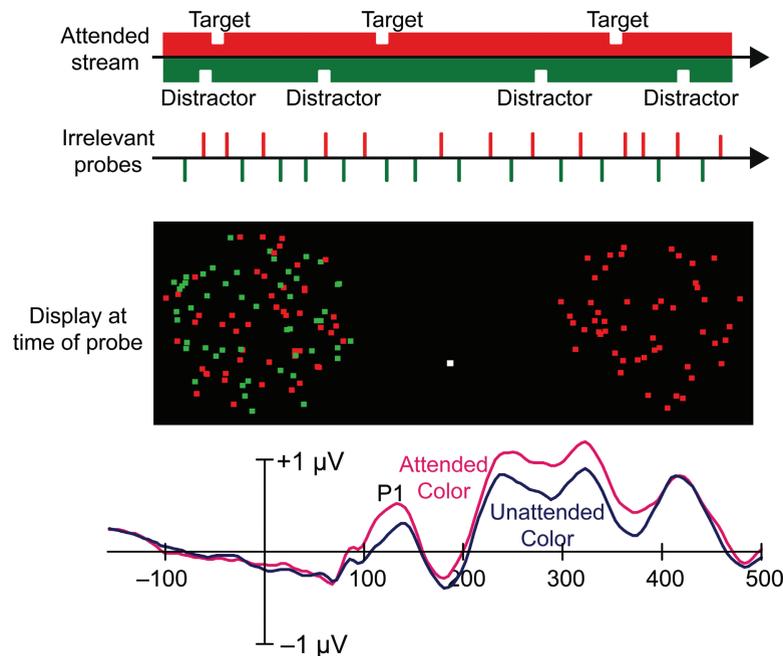


Fig. 11.9. Stimuli and grand average ERP waveforms from the study of Zhang and Luck (2009). Adapted with permission from Zhang and Luck (2009).

1 a follow-up experiment was conducted in which the  
 2 attended stimulus stream consisted of a sequence of  
 3 all-red dots and all-green dots rather than a stream  
 4 of simultaneously interdigitated red and green dots.  
 5 Under these conditions, the probes did not elicit a  
 6 larger P1 when the probe color matched the attended  
 7 color. Thus, simultaneous competition appears to  
 8 be the key factor needed to observe early location-  
 9 independent effects of featural attention.

10 It is not yet known whether these color-based  
 11 P1 attention effects reflect a modulation of the  
 12 same underlying ERP component as the previously  
 13 observed location-based P1 attention effects. The  
 14 timing and scalp distributions are at least grossly  
 15 similar, but it is difficult to demonstrate that ERP  
 16 effects observed in separate experiments actually  
 17 arise from the same component (see Chapter 1, this  
 18 volume). Thus, it is not yet possible to conclude  
 19 that spatial and featural attention operate in exactly  
 20 the same way. In addition, simultaneous competi-  
 21 tion does not appear to be necessary to observe  
 22 location-based P1 attention effects, so location may  
 23 still have a special status in attention.

#### 24 **Object-Based Visual Attention**

25 In naturally occurring visually guided behavior,  
 26 humans rarely focus attention on a peripheral  
 27 location in anticipation of stimuli that might

28 subsequently appear in that location. Instead, atten-  
 29 tion is usually directed to objects. Consider the exam-  
 30 ple shown in Figure 11.10, in which attention might  
 31 be directed to the apple. Identifying the apple requires  
 32 separating it from the background, including the leaf  
 33 that partially occludes the top of the apple. Thus, it  
 34 is ultimately the object we wish to select rather than  
 35 a region of space. The behavioral attention literature  
 36 has extensively examined the issue of *object-based*  
 37 attention, demonstrating that the allocation of atten-  
 38 tion is influenced by the nature of the objects in the  
 39 visual input (see especially Driver & Baylis, 1989;



Fig. 11.10. Example of the need for object-based attentional selection in the perception of natural images.

1 Duncan, 1984; Egly et al., 1994; Kahneman et al.,  
 2 1992; Vecera, 1994). As discussed by Vecera and  
 3 Farah (1994), object-based attention could work in  
 4 two ways. First, attention could operate on high-  
 5 level object representations that have been abstracted  
 6 away from specific spatial locations, such as the geon  
 7 structural description representations proposed by  
 8 Biederman (1987). In the example shown in Fig-  
 9 ure 11.10, this would involve forming a location-  
 10 independent representation of the apple. Second,  
 11 mechanisms of perceptual organization could link  
 12 the micro elements of an object together into a spatial  
 13 region that reflects the boundaries of the object, and  
 14 attention could spread throughout this region. In the  
 15 example shown in Figure 11.10, this would involve  
 16 the spread of attention throughout the region defined  
 17 by the apple.

18 Although object-based attention has been a topic  
 19 of extensive research in the behavioral literature, it  
 20 has been largely ignored by ERP researchers. Two  
 21 studies have recorded ERPs in variants of the object-  
 22 based attention paradigm of Egly et al. (1994). Fig-  
 23 ure 11.11 illustrates the task used for one of these  
 24 studies (He et al., 2004). The display contains either  
 25 two vertical bars or two horizontal bars. One end of  
 26 one of the bars is cued, and a subsequent target is  
 27 usually presented at the cued location (valid trials). In  
 28 invalid trials, the target can be presented within the  
 29 same rectangle as the cue (as shown in Figure 11.11)  
 30 or at an equally distant location within the other  
 31 rectangle. Reaction times (RTs) in this paradigm are  
 32 fastest when the target appears at the cued location,  
 33 slowest when the target appears at an uncued location

34 within the uncued rectangle, and intermediate when  
 35 the target appears at the uncued location within the  
 36 cued rectangle. The faster RTs for the uncued loca-  
 37 tion within the cued rectangle compared to the equi-  
 38 distant uncued location within the other rectangle  
 39 are generally taken as evidence that attention “spreads”  
 40 throughout the cued object. He et al. (2004) found  
 41 that the N1 wave elicited by the target showed an  
 42 analogous pattern: N1 amplitude was greatest for  
 43 targets presented at the cued location, smallest for  
 44 targets presented at the uncued location within the  
 45 uncued rectangle, and intermediate for targets pre-  
 46 sented at the uncued location within the cued rect-  
 47 angle. The P1 wave, however, showed a pure spatial  
 48 attention effect. That is, it was larger for targets pre-  
 49 sented at the cued location than for targets presented  
 50 at the uncued locations, and it did not differ between  
 51 the uncued locations in the cued and uncued rectan-  
 52 gles. This same pattern was replicated in a study that  
 53 included both ERPs and fMRI (Martinez et al.,  
 54 2006), and the fMRI data suggested that the object-  
 55 based and space-based components portions of the  
 56 N1 attention effect both came from the same region  
 57 of lateral occipital cortex. This is consistent with the  
 58 proposal that object-based attention reflects a spatial  
 59 spreading of attention within an object’s boundaries.

### Postperceptual Attention Effects

60 The studies described thus far have focused on the  
 61 role of attention in the perception of stimuli. However,  
 62 selective attention may also operate on postperceptual  
 63 processes<sup>4</sup> (for a detailed discussion, see Luck &  
 64 Vecera, 2002). Generally speaking, attention appears  
 65

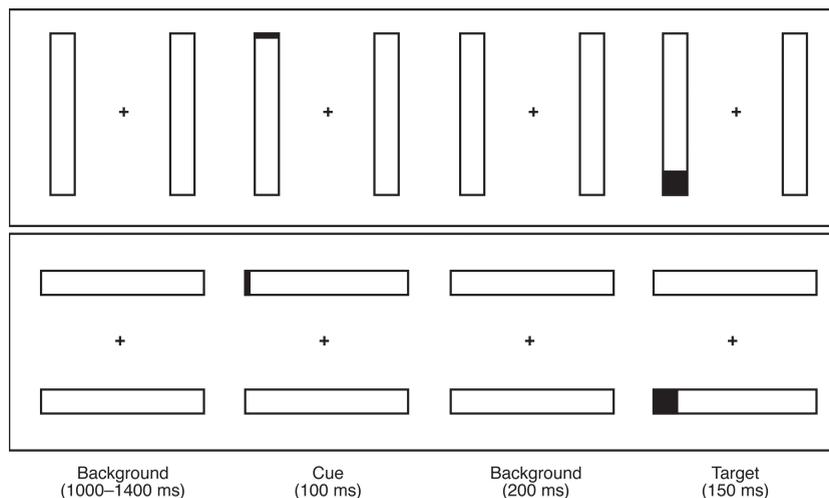


Fig. 11.11. Example stimuli from the study of He et al. (2004).

1 to operate within a given system when that system is  
 2 overloaded (Lavie, 1995; Lavie & Cox, 1997; Lavie  
 3 et al., 2004; Luck & Hillyard, 1999; Luck & Vecera,  
 4 2002). When multiple competing sensory inputs  
 5 occur simultaneously or in rapid sequence, perceptual  
 6 systems are overloaded and attention operates at an  
 7 early stage to limit perceptual processing to a subset  
 8 of the information. Under these conditions, atten-  
 9 tion influences the early sensory ERP components.  
 10 However, it is possible to create situations in which  
 11 the stimuli do not overload perceptual systems but  
 12 overload memory encoding or response selection sys-  
 13 tems. In these tasks, all items are perceived but only a  
 14 subset of the items are stored in memory or lead to  
 15 behavioral responses, and this is accompanied by  
 16 changes in ERP components that reflect memory-  
 17 and response-related processes. The proposal that  
 18 attention can operate at both early and late stages,  
 19 depending on the nature of the stimuli and task, is  
 20 called the *flexible selection* hypothesis (Vogel et al.,  
 21 2005). In the following sections, we will discuss tasks  
 22 in which attention modulates the N400 component,  
 23 the P3 or P300 component, and the lateralized readi-  
 24 ness potential (LRP). We will begin with studies that  
 25 focus directly on the attention sensitivity of these  
 26 components and then discuss studies that have used  
 27 these components as a tool to answer broader ques-  
 28 tions about attention.

29 ***Attention and the N400 Component***

30 The N400 component is elicited by stimuli that  
 31 mismatch a previously established semantic context  
 32 (see Chapter 15, this volume). Consider, for example,  
 33 a sentence that begins “John put on his glasses and  
 34 started to read a . . .” If this sentence ends with “book,”  
 35 then this final word will match the semantic context  
 36 and generate very little N400 activity. If, however, this  
 37 sentence ends with “mattress,” then this final word  
 38 will mismatch the context and generate a large N400.  
 39 Similar effects can be obtained with simple word  
 40 pairs. For example, the second word in the pair will  
 41 elicit a small N400 for “read . . . book” but will elicit  
 42 a large N400 for “read . . . mattress.” This difference  
 43 between an initial word or phrase and a subsequent  
 44 target word is termed the *N400 priming effect*.

45 Three things are logically necessary for a subject  
 46 to exhibit an N400 priming effect. First, the subject  
 47 must understand and retain the information about  
 48 the prime word or phrase. Second, the subject must  
 49 identify the target word fully, at least to the point of  
 50 lexical access. Third, the subject must actually com-  
 51 pare the target word with the prime. All three of  
 52 these steps can be influenced by attention.

53 The most basic way to manipulate attention in  
 54 the context of words is to vary whether the task  
 55 requires semantic processing of the words. Several  
 56 studies have used such task manipulations to ask  
 57 whether word recognition is automatic. For exam-  
 58 ple, Kutas and Hillyard (1989) presented subjects  
 59 with pairs of words followed by a single letter and  
 60 asked the subjects to report whether that letter had  
 61 been present in either of the words. The N400 was  
 62 larger when the second word in each pair was seman-  
 63 tically unrelated to the first word compared to when  
 64 the two words were related, even though the mean-  
 65 ings of the words were irrelevant to the task. Similarly,  
 66 Connolly et al. (1990). presented spoken sentences  
 67 and tested conditions in which the subjects were  
 68 required (1) to simply listen to the sentences, (2) to  
 69 detect whether a specific speech sound was in the  
 70 final word of each sentence, or (3) to decide whether  
 71 the final word of each sentence belonged to a specific  
 72 semantic category. An equivalently large N400 was  
 73 elicited by the final word of the sentences in all three  
 74 conditions, despite the differences in the semantic  
 75 requirements of the tasks.

76 Results of this nature might be taken as evidence  
 77 that word identification is automatic. However, the  
 78 perceptual load was so low in these experiments that  
 79 subjects may have had sufficient cognitive resources  
 80 to identify the meanings of the words while simulta-  
 81 neously performing the instructed task. And given  
 82 that the instructed tasks were quite boring, the sub-  
 83 jects may have engaged in semantic processing  
 84 simply to reduce their level of boredom. To demon-  
 85 strate that a process is automatic, one must go  
 86 beyond showing that it occurs when it is not required;  
 87 one must also show that it occurs when subjects are  
 88 strongly motivated to avoid it (see Jonides, 1981).  
 89 Heil et al. (2004) took a step in this direction by  
 90 using a more difficult task to direct attention away  
 91 from the meanings of the words. Specifically, they  
 92 presented word pairs and asked subjects to detect  
 93 whether the first word (the prime) contained a  
 94 specific target letter and whether the second word  
 95 (the target) was a real word or a pseudoword. The  
 96 letter-search task for the prime word was designed to  
 97 motivate subjects to ignore the meaning of this word  
 98 and instead focus on its orthography. The N400 elic-  
 99 ited by the target word was found to be larger when  
 100 it was semantically unrelated to the prime than  
 101 when it was semantically related. From this, Heil  
 102 et al. (2004) concluded that subjects automatically  
 103 extracted the meaning of the prime word. However,  
 104 the N400 difference between related and unrelated  
 105 trials was small compared to the N400 difference

1 typically observed in studies in which subjects actively  
 2 attend to the word meanings (and the Heil et al. study  
 3 did not contain a condition in which the word mean-  
 4 ings were relevant). Thus, it is entirely possible that  
 5 the letter-search task was not sufficiently demanding  
 6 to completely eliminate semantic processing of the  
 7 prime. Indeed, as we will describe below, other atten-  
 8 tional manipulations have eliminated the N400  
 9 priming effect, suggesting that semantic analysis is  
 10 not fully automatic. Thus, it is important not to use  
 11 the lack of an attention effect for a given ERP compo-  
 12 nent to draw conclusions about the automaticity of  
 13 that component unless a very strong manipulation of  
 14 attention has been used.

15 **Attention and the P3 Component**

16 The P3 component is typically elicited by infrequent  
 17 task-relevant events (see Chapter 7, this volume).  
 18 There is no universally accepted theory of the P3  
 19 wave, but the most common view—proposed origi-  
 20 nally by Donchin (1981)—is that the P3 wave  
 21 reflects an updating of *context* information. Most  
 22 researchers assume that *context* is equivalent to *work-*  
 23 *ing memory*, but Donchin (1981) never made this  
 24 claim. Nevertheless, researchers outside the ERP  
 25 domain often treat *context* and *working memory* as  
 26 equivalent concepts (e.g., Cohen et al., 1990), and  
 27 the P3 wave has been used frequently as an index  
 28 of working memory updating (e.g., Vogel et al.,  
 29 1998).

30 Regardless of what process the P3 represents,  
 31 there is clear evidence that P3 amplitude can be  
 32 influenced by that amount of attention allocated to  
 33 a stimulus. This is most clearly observed in dual-task  
 34 experiments in which subjects are instructed to vary  
 35 the relative allocation of attention between the two  
 36 tasks. For example, Isreal et al. (1980b) asked sub-  
 37 jects to perform an auditory oddball task, in which  
 38 they mentally counted infrequent target tones,  
 39 simultaneously with an air traffic control task in  
 40 which they tracked either four or eight moving  
 41 objects on a video screen. An increase in the number  
 42 of objects being tracked increases the resources  
 43 required for this task, which should in turn reduce  
 44 the resources available for the auditory oddball task.  
 45 Isreal et al. found that P3 amplitude for the infre-  
 46 quent target tones was reduced when the subjects  
 47 tracked eight objects compared to four objects in  
 48 the visual tracking task, consistent with the hypoth-  
 49 esis that the amplitude of the P3 wave elicited by a  
 50 given stimulus depends on the amount of resources  
 51 available to process that stimulus (see also Isreal  
 52 et al., 1980a; Kramer et al., 1983; Mangun &

Hillyard, 1990; but see Kok, 2001, for caveats on  
 the use of P3 as a measure of processing capacity).

**The Attentional Blink Paradigm**

The P3 and N400 components have been very  
 useful in understanding the operation of attention  
 in the *attentional blink* paradigm, in which subjects  
 must discriminate two targets that appear in close  
 succession. A typical attentional blink task is shown  
 in Figure 11.12. Each trial consists of a sequence of  
 letters presented very rapidly at fixation (one letter  
 every 100 ms); two of the letters are red and must be  
 reported at the end of the trial. The lag between the  
 first target (*T1*) and the second target (*T2*) varies  
 across trials (e.g., *lag 2* means that *T2* was the second  
 item after *T1*). If *T1* and *T2* are presented close  
 together in time, attention may still be directed to  
*T1* when *T2* appears, making it difficult for the sub-  
 ject to report *T2*. This is called the *attentional blink*  
 because it is as if *T1* triggers a brief blink of atten-  
 tion, causing *T2* to be missed. In most cases, this  
 blink is triggered slowly enough that *T2* is reported  
 correctly when it is the item immediately following  
*T1* (i.e., at lag 1). Thus, *T2* accuracy is usually high  
 at lag 1, drops to its lowest point at lag 3, and recov-  
 ers by approximately lag 6 or 7 (see Figure 11.12).  
 Many attentional blink studies also include a  
*T2*-only control condition, in which subjects ignore  
*T1* and only report *T2*. In this condition, perfor-  
 mance is largely independent of the *T1*–*T2* lag.

The study that coined the term *attentional blink*  
 assumed that subjects essentially failed to see *T2*  
 during the attentional blink period (Raymond et al.,  
 1992). However, the visual system can discriminate  
 complex scenes within 100–150 ms (Potter, 1976;  
 Thorpe et al., 1996), so it should be able to dis-  
 criminate relatively simple, highly discriminable,  
 highly familiar stimuli such as letters even more rap-  
 idly. The attentional blink paradigm does not merely  
 require perception of the two targets; the targets  
 must also be stored in working memory so that they  
 are not overwritten by the subsequent stimuli and  
 can be reported at the end of the trial. It is therefore  
 possible that *T2* is identified but cannot be trans-  
 ferred to working memory when attention is occu-  
 pied by *T1*. Indeed, Giesbrecht and Di Lollo (1998)  
 showed that the perceptual representation of *T2*  
 is overwritten by the next item in the stimulus  
 sequence during the attentional blink.

Event-related potentials have been used deter-  
 mine whether observers fail to report *T2* correctly  
 during the attentional blink period because they fail  
 to see it or because they fail to encode it in working

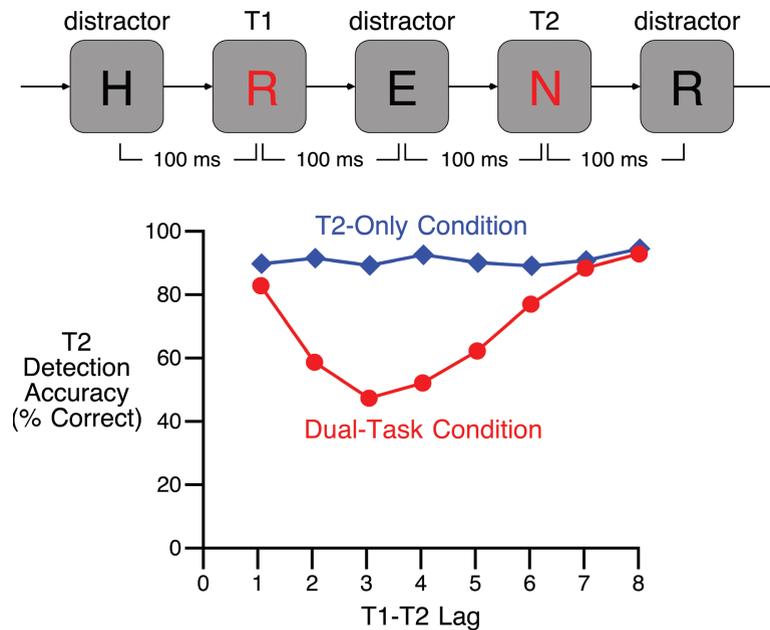


Fig. 11.12. Typical stimuli and results from the attentional blink paradigm.

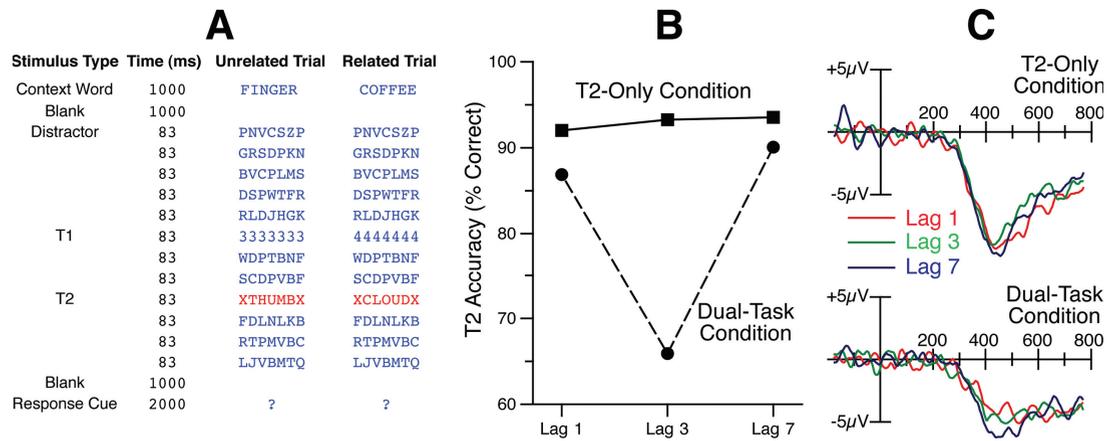
1 memory (Luck et al., 1996; Vogel et al., 1998). The  
 2 first experiment in this study examined the P1 and  
 3 N1 components as measures of sensory processing,  
 4 finding no reduction in amplitude for stimuli during  
 5 the attentional blink period. This result indicated  
 6 that these stages of sensory processing were not  
 7 influenced by the attentional blink, but it is always  
 8 possible that attention influenced some sensory pro-  
 9 cess that did not have an ERP signature.

10 To definitively show that the attentional blink  
 11 represents a postperceptual effect of attention, it was  
 12 necessary to provide evidence that T2 was fully iden-  
 13 tified during the attentional blink period. However,  
 14 there is no sensory ERP component that clearly  
 15 reflects the *endpoint* of perception (if, indeed, there is  
 16 such a thing). To solve this problem, Luck et al.  
 17 (1996) employed a “trick of the trade,” in which an  
 18 ERP component is used as an index of the processes  
 19 that necessarily precede it rather than the processes  
 20 that directly generate the component. For example,  
 21 as discussed in Chapter 9 of this volume, the subtraction  
 22 procedure used to isolate the LRP guarantees  
 23 that the voltage cannot exceed zero until the brain  
 24 has determined which response is appropriate for the  
 25 present stimulus. Thus, even though the LRP does  
 26 not itself directly reflect the process of determining  
 27 which response is appropriate, its latency can be used  
 28 to measure the time required to make this determina-  
 29 tion. In the case of the attentional blink, the N400

component can be used in a similar manner to deter-  
 mine whether a word has been fully identified, even  
 though the N400 component itself does not directly  
 reflect word identification processes.

The logic behind this use of the N400 is as fol-  
 lows. When a given word is semantically unrelated  
 to a previously established semantic context, that  
 word will elicit a larger N400 than if the word is  
 related to the context (e.g., in the context of *coffee*,  
 the word *cream* is related and the word *cloud* is not).  
 To generate a larger response for an unrelated word  
 than for a related word, the brain must have already  
 extracted the identity of the word (i.e., lexical access  
 must have occurred). If the brain had not identified  
 the word, how could it compare it to the semantic  
 context and determine whether it matched or mis-  
 matched? Thus, the presence of a larger N400 for an  
 unrelated word than for a related word implies that  
 the brain must have identified the words. Thus, the  
 presence of a larger N400 for unrelated words than  
 for related words during the attentional blink would  
 indicate that these words had been identified to a  
 high level.

To implement this idea in an attentional blink  
 experiment, Luck et al. (1996) preceded each trial  
 with a 1000 ms *context word*, which the subjects  
 simply stored in memory for that trial (see Fig-  
 ure 11.13A). After a 1000 ms delay, a stimulus stream  
 was presented at a rate of 12 stimuli per second.



**Fig. 11.13.** Stimuli (A), behavioral results (B), and grand average ERP waveforms from the attentional blink study of Luck et al. (1996). The ERP waveforms are difference waves, formed by subtracting the ERP waveform elicited by T2 on related trials from the ERP waveform elicited by T2 on unrelated trials.

1 Most of the items in this stream were seven-character  
 2 consonant strings, which served as distractors.  
 3 T1 was a digit, repeated seven times to make a seven-  
 4 character string. T2 was a word that was either  
 5 semantically related or semantically unrelated to the  
 6 context word for that trial (and was flanked by Xs to  
 7 make a seven-character string). All of the strings were  
 8 drawn in blue, except that T2 was drawn in red to  
 9 ensure that there would be no ambiguity about which  
 10 word was T2 and to ensure good time locking in  
 11 the ERPs. At the end of each trial, the subjects were  
 12 instructed to make one button-press response to indi-  
 13 cate whether T1 was an odd or even number and  
 14 then to make a second button-press response to indi-  
 15 cate whether T2 was semantically related or unrelated  
 16 to the context word for that trial. This was the *dual-*  
 17 *task* condition of the experiment. As is common, the  
 18 experiment also included a *T2-only* condition, in  
 19 which subjects ignored T1 and made only the T2  
 20 response on each trial. In both conditions, T2 was  
 21 either the first item following T1 (*lag 1*), the third  
 22 item following T1 (*lag 3*), or the seventh item follow-  
 23 ing T1 (*lag 7*). Given the number of trials that must  
 24 be averaged together to obtain clean ERP waveforms,  
 25 it was not possible to test every lag, but lags 1, 3, and  
 26 7 provide the most important information because  
 27 the attentional blink typically consists of a drop in  
 28 performance between lag 1 and lag 3 with a recovery  
 29 by lag 7.  
 30 In the T2-only condition, subjects were expected  
 31 to have no trouble identifying T2 at any lag, leading  
 32 to high levels of behavioral accuracy at all lags. Thus,  
 33 the N400 was expected to be much larger when T2  
 34 mismatched the context word than when it matched  
 35 the context word in this condition, irrespective of

lag. In the dual-task condition, behavioral perfor-  
 mance for T2 was expected to drop at lag 3, indicat-  
 ing that subjects could not report whether T2 was  
 related or unrelated to the context word at this lag  
 (which is the typical attentional blink pattern).  
 If this decrement in behavioral performance occurs  
 because subjects cannot identify T2 during the  
 attentional blink period, then the N400 should be  
 eliminated for T2 during the attentional blink.  
 If, however, subjects can identify T2 during the  
 N400 but fail to store it in working memory, then  
 the brain would still be able to compare T2 with the  
 context word and generate a larger N400 when T2  
 was unrelated than when it was related.  
 The behavioral results are shown in Figure  
 11.13B. As is typical in attentional blink experi-  
 ments, T2 accuracy was high at all lags in the  
 T2-only condition, but it dropped substantially at  
 lag 3 in the dual-task condition. The ERP results  
 are shown in Figure 11.13C. These ERPs are differ-  
 ence waves formed by subtracting the waveforms  
 when T2 was semantically related to the context  
 word from the waveforms when T2 was semanti-  
 cally unrelated to the context word. This subtrac-  
 tion was important for two reasons. First, it iso-  
 lated the brain's differential response to unrelated  
 versus related words, eliminating any ERP activity  
 related to other aspects of the processing of the  
 stimuli. Second, it subtracted away the overlapping  
 ERPs from the other stimuli in the stream. The  
 resulting difference wave was somewhat larger in  
 the T2-only condition than in the dual-task con-  
 dition, which presumably reflects the general  
 difficulty of coordinating two tasks in the dual-  
 task condition. The key result is that the differ-  
 ence wave was not reduced

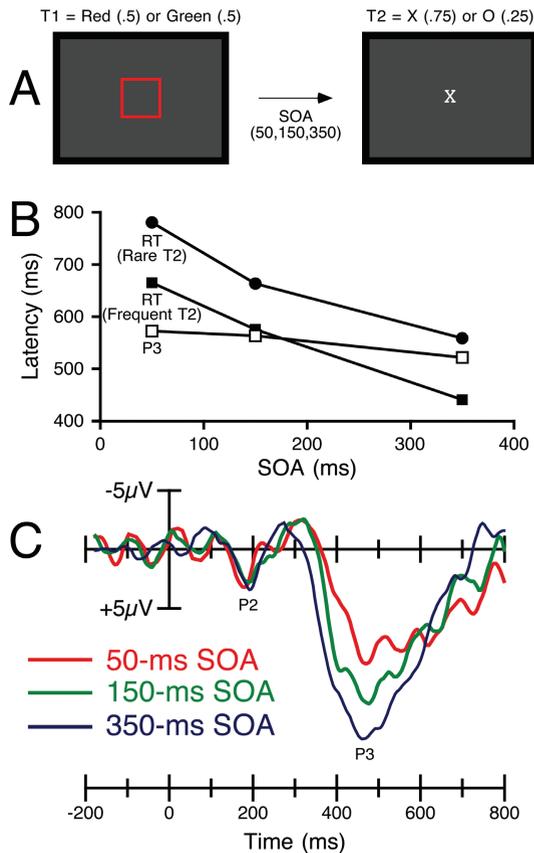
1 in amplitude at lag 3 in the dual-task condition.  
 2 That is, even though subjects were quite inaccurate  
 3 in overtly reporting whether T2 was related or unre-  
 4 lated to the context word at lag 3 of this condition,  
 5 their brains clearly made this discrimination well  
 6 enough to generate a larger N400 for unrelated  
 7 words than for related words. Thus, T2 is identified  
 8 during the attentional blink period and the word  
 9 identity is compared with the previously established  
 10 semantic context, generating an N400 if the word  
 11 does not match this context. However, this infor-  
 12 mation either fails to reach awareness or is immedi-  
 13 ately forgotten.

14 It is conceivable that T2 was discriminated  
 15 poorly during the attentional blink period, but  
 16 that N400 amplitude is simply insensitive to the  
 17 quality of the discrimination. To rule out this possi-  
 18 bility, Vogel et al. (1998) ran a control experiment  
 19 with the T2-only task in which varying levels of  
 20 visual noise were added to the T2 word. It is well  
 21 known that adding this sort of noise impairs the  
 22 perceptual discriminability of visual stimuli. Indeed,  
 23 discrimination accuracy decreased systematically as  
 24 the noise level increased. The amplitude of the  
 25 N400 difference wave also decreased systematically  
 26 as the noise level increased, demonstrating that  
 27 N400 amplitude is indeed sensitive to reductions in  
 28 perceptual quality. Thus, the lack of a reduction in  
 29 N400 amplitude during the attentional blink period in the main experiment provides strong evi-  
 30 dence that the attentional blink does not reflect a  
 31 reduction in perceptual discriminability (but see  
 32 Giesbrecht et al., 2007, for conditions under which  
 33 perception can be influenced by the attentional  
 34 blink).

35 A leading hypothesis is that the attentional blink  
 36 reflects a failure to store T2 in working memory,  
 37 such that the representation of T2 is overwritten by  
 38 the subsequent stimulus (Giesbrecht & Di Lollo,  
 39 1998). To test this hypothesis, Vogel et al. (1998)  
 40 ran an experiment in which T2 was either a fre-  
 41 quently occurring stimulus category or a rare stimu-  
 42 lus category. The P3 wave was isolated with a  
 43 rare-minus-frequent difference wave. The P3 dif-  
 44 ference wave was found to be completely eliminated  
 45 during the attentional blink period. If the P3 wave  
 46 reflects working memory encoding, as discussed  
 47 above, then this finding provides support for the  
 48 hypothesis that working memory encoding is dis-  
 49 rupted during the attentional blink (for additional  
 50 evidence from the P3 wave, see Vogel & Luck,  
 51 2002).

**The Psychological Refractory Period Paradigm**

53  
 54  
 55 The psychological refractory period (PRP) paradigm  
 56 is similar to the attentional blink paradigm, except  
 57 that immediate responses are made to the two tar-  
 58 gets and RT rather than accuracy is the main depen-  
 59 dent variable. In a typical PRP experiment, subjects  
 60 are presented with two targets (again called T1  
 61 and T2) on each trial (but without any additional  
 62 distractor stimuli). The time between the onset of  
 63 T1 and the onset of T2 is varied (the *stimulus onset*  
 64 *asynchrony* or *SOA*). When the SOA between T1  
 65 and T2 is long, subjects are finished processing T1  
 66 by the time T2 is presented, and the RT for T2 is  
 67 short. When the SOA between T1 and T2 is short,  
 68 however, T1 is still being processed when T2 is pre-  
 69 sented, and the RT for T2 is prolonged. A leading  
 70 theory proposes that the prolonged RTs at short



**Fig. 11.14.** Stimuli (A), behavioral results (B), and grand average ERP waveforms from the psychological refractory period study of Luck (1998). The ERP waveforms are difference waves, formed by subtracting the ERP waveform elicited by the frequent T2 stimulus from the ERP waveform elicited by the rare T2 stimulus.

SOAs are primarily a result of a bottleneck in the response selection process (i.e., the process of determining which response is appropriate once the stimulus has been identified). That is, the early stages of T2 processing can be carried out while subjects are still processing T1, but the response selection process for T2 cannot begin until the response selection process for T1 has finished (see the review by Pashler, 1994). Processing at other stages may also compete for limited processing resources, but this theory proposes that response selection is the only *single-channel* process (i.e., the only process that must be postponed for one stimulus if it is busy for another stimulus).

Event-related potentials have been used to test this proposal, examining the P3 wave (Arnell et al., 2004; Dell'Acqua et al., 2005; Luck, 1998b) and the LRP (Osman & Moore, 1993). The P3 wave is a sensitive index of stimulus evaluation time (see Chapter 7, this volume), and Pashler's (1994) bottleneck model would predict that stimulus evaluation is not postponed in the PRP paradigm. To isolate the P3 wave for T2 from other T2-related components and the overlapping T1 ERP waveform, studies have used rare and frequent T2 stimuli. In the study of Luck (1998), for example, T1 was either a red or a green square (with equal probabilities) and T2 was either an *X* or an *O* (with one being 75% probable and the other being 25% probable; see Figure 11.14A). The RT for T2 dropped steeply as the SOA between T1 and T2 increased, as is typical in PRP experiments, and this effect was the same for the rare and frequent T2 alternatives (see Figure 11.14B). The P3 wave was isolated by means of difference waves in which the ERP response to the frequent T2 was subtracted from the ERP response to the rare T2 (see Figure 11.14B). When the SOA became short, P3 amplitude was somewhat reduced and P3 latency was somewhat prolonged. However, the slowing of P3 latency was much less pronounced than the slowing of RT. These findings are consistent with the proposal that the increase in RT at short SOAs is not primarily caused by a slowing of the processes involved in perceiving and categorizing T2 (although there may be some competition for limited resources in these processes).

To provide evidence that response selection is the major locus of slowing in this paradigm, Osman and Moore (1993) examined the LRP, which reflects the difference in voltage between electrodes contralateral and ipsilateral to the hand of response (see Chapter 9, this volume). The LRP cannot be generated until the subject has determined which

hand is appropriate for the given stimulus; that is, it cannot be generated until the response selection process has occurred. Osman and Moore found that the LRP was substantially delayed at short SOAs and was also reduced in amplitude. Importantly, the LRP peaked approximately 100 ms prior to the response at all SOAs, indicating that all of the slowing in RT could be explained by a slowing of the LRP. Together, the results of this study and of the Luck (1998) study provide strong evidence that the PRP is caused by a slowing of response selection (indexed by the LRP), with only modest interference with perception and categorization (indexed by the P3).

## Notes

- 1 It should be noted that a very large number of trials must be averaged together to obtain a sufficient signal-to-noise ratio to observe reliable effects of attention on the early visual components, which are often well under 1  $\mu$ V. In most cases, at least 200 trials must be averaged together in each waveform for each subject, and studies that require high signal-to-noise ratios (e.g., localization studies) may need over 1000 trials per waveform (see, e.g., Di Russo et al., 2003a).
- 2 Positive and negative for these dipoles reflect the polarity observed at the scalp for the corresponding ERP components and do not indicate anything about excitatory versus inhibitory activity.
- 3 A posterior selection positivity is sometimes observed beginning at around 100 ms in color-based attention experiments (see, e.g., the IPz site in Figure 11.7), and this effect partially overlaps with the P1 wave (Anllo-Vento et al., 1998; Zhang & Luck, 2009). However, the timing and scalp distribution of this effect indicate that it is not a modulation of the P1 wave.
- 4 The term *perception* is sometimes used to refer to a conscious experience of sensory inputs and is sometimes used simply to denote the late stages of sensory processing. For example, there is a large area of research on the topic of *perception without awareness*, which presupposes that perception could potentially be dissociated from conscious experience. Here we use the term *perception* in this latter sense, corresponding to the process of linking a sensory input with categories based on experience (e.g., determining that a particular sensory input is a horse rather than a cow, a fork, a pebble, etc.). Postperceptual processes, therefore, are those that operate on representations of sensory inputs that have already been categorized in this manner.

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