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On the utility of P3 amplitude as a measure of processing capacity

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Abstract

The present review focuses on the utility of the amplitude of P3 of as a measure of processing capacity and mental workload. The paper starts with a brief outline of the conceptual framework underlying the relationship between P3 amplitude and task demands, and the cognitive task manipulations that determine demands on capacity. P3 amplitude results are then discussed on the basis of an extensive review of the relevant literature. It is concluded that although it has often been assumed that P3 amplitude depends on the capacity for processing task relevant stimuli, the utility of P3 amplitude as a sensitive and diagnostic measure of processing capacity remains limited. The major factor that prompts this conclusion is that the two principal task variables that have been used to manipulate capacity allocation, namely task difficulty and task emphasis, have opposite effects on the amplitude of P3. I suggest that this is because, in many tasks, an increase in difficulty transforms the structure or actual content of the flow of information in the processing systems, thereby interfering with the very processes that underlie P3 generation. Finally, in an attempt to theoretically integrate the results of the reviewed studies, it is proposed that P3 amplitude reflects activation of elements in a event-categorization network that is controlled by the joint operation of attention and working memory.

Descriptors: ERP, P3 amplitude, P3 latency, Task difficulty, Attention, Capacity, Processing resources

Probably no psychophysiological measure has received as much attention from researchers in the last two decades as the P3 component of the event-related potential (ERP). There is general agreement that P3 is not a unitary brain potential but represents the summation of activity from various widely distributed areas in the brain (see Johnson, 1993 and Paller, 1994 for a review of human and animal studies, respectively). It is also generally accepted that a distinction can be made between two subcomponents, namely the novelty P3 and the target P3 (P3b, or "classical" P3). Novelty P3 is a large, positive deflection with a frontocentral distribution that is elicited by novel, nontarget stimuli and that mainly reflects involuntary attention shifts to changes in the environment (Friedman & Simpson, 1994; Spencer, Dien, & Donchin, 1999). It is functionally related to another subcomponent, P3a, that seems to be more specifically related to deviant auditory nontarget events (Squires, Squires, & Hillyard, 1975). In contrast, the P3b (the component that is the focus of the present review, and that will further be referred to as P3) has a more posterior-parietal scalp distribution and a somewhat longer latency than novelty P3 and P3a. P3b has been regarded as a sign of processes of memory access that are evoked by evaluation of stimuli in tasks that require some form of action like a covert or overt response (Donchin, Kramer, & Wickens, 1986).

Although early studies of P3 were mainly concerned with validating the construct underlying P3, later studies have focused more strongly on the application of this measure as a tool in cognitive science. One of the important insights of the last decades has been that components of the event-related potentials like P3 can augment the information provided by performance measures in the study of human information processing (Coles & Gratton, 1986; Rugg & Coles, 1995). In particular P3 studies were driven by the notion that the information processing sequence can be broken down in two portions, stimulus and response related processes, with variation in P3 latency and amplitude representing variations in demands on stimulus related processes.

P3 Latency

A general consensus seems to have emerged from earlier studies that P3 is evoked after the stimulus has been evaluated.[1] The concept stimulus evaluation has been used by most ERP researchers in a generic sense: It refers to all processes in the information-processing stream that occur prior to selection and preparation of motor responses. A frequently observed phenomenon has been that P3 latency increases when categorization of the stimulus becomes more difficult (Coles, Smid, Scheffers, & Otten, 1995; Courchesne, Hillyard, & Courchesne, 1977; Kutas, McCarthy, & Donchin, 1977). Some studies have also reported that P3 latency is more

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[1] The term stimulus evaluation does not necessarily imply that the subject has fully extracted all task relevant information. For instance, it is conceivable that in conditions that create a data limitation (such as a low perceptual quality of the stimulus or high time pressure) or when the subject follows a strategy that favors speed above accuracy, P3 can also be emitted on the basis of partial information (see also Coles, Gratton, Bashore, Eriksen, & Donchin, 1985).

dependent on perceptual variables than on a task manipulation like stimulus–response compatibility. The latter task variable has a large effect on reaction time and is assumed to influence primarily the stage of response selection (Magliero, Bashore, Coles, & Donchin, 1984; McCarthy & Donchin, 1981; Smid, Mulder, Mulder, & Brands, 1992; Smulders, Kok, Kenemans, & Bashore, 1995; Verleger, 1997).

The insights provided by the earlier studies were of great importance for making inferences from P3 latency in a series of experiments that aimed at solving controversies concerning the "locus of effect" of experimental variables on reaction time. These studies concerned the "interference" effect in the Eriksen flanker task (Eriksen & Eriksen, 1974), the "Simon effect" in spatial compatibility tasks, the "Stroop effect" in semantic compatibility tasks, and the "load effect" in Sternberg tasks. The principal finding of these studies was that interference effects were much stronger for reaction time (or response related ERP measures) than for P3 latency measures. On the basis of results of the earlier P3 latency studies it was further suggested that response-related processes were the probable locus of the interference effect (e.g., Coles, 1989; Duncan-Johnson & Kopell, 1981; Ford, Roth, Mohs, Hopkins, & Kopell, 1979; Osman, Bashore, Coles, Donchin, & Meyer, 1992; Zeef & Kok, 1992b; Zeef, Sonke, Kok, Buiten, & Kenemans, 1996).

P3 Amplitude

In contrast with P3 latency that reflects timing of mental processes, P3 amplitude has been considered to be more closely related to the intensity of processing (Donchin, Karis, Bashore, Coles, & Gratton, 1986; Donchin, Kramer, & Wickens, 1986; Kok, 1990; Polich & Kok, 1995). Furthermore, a number of P3 researchers have explicitly or implicitly assumed that P3 amplitude reflects demands on "perceptual-central" resources (see Donchin, Kramer, et al., 1986, Kramer & Spinks, 1991).[2] The term perceptual-central resources is derived from the multiple capacity framework that has been proposed by Wickens (1980, 1984) and that involves three separate dimensions: stages of processing, codes, and modalities. The similarity of tasks within this three-dimensional space determined the amount of interference between these tasks. With respect to stages of processing, it was further proposed that perceptual and central processing relied on common resources, which in turn were functionally independent from resources associated with response processes (Figure 1). Wickens' view clearly deviated from earlier conceptualizations of resources in terms of a single central pool of attentional capacity that can be applied to tasks of all types (Kahneman, 1973; Norman & Bobrow, 1975; Shiffrin & Schneider, 1977).

The hypothesis that P3 amplitude is diagnostic for perceptual/central as opposed to response-related processing is mainly based upon the results of dual-task studies suggesting that the relationship between P3 amplitude and task demands occurred only when these demands where perceptual/cognitive in nature (Isreal, Chesney, Wickens, & Donchin, 1980; Isreal, Wickens, Chesney, & Donchin, 1980; Sirevaag, Kramer, Coles, & Donchin, 1989; Wickens, Kramer, Vanasse, & Donchin, 1983). Another factor that contributed to the latter interpretation of P3 was the findings of P3 latency studies described above. Especially the seminal studies of Kutas et al. (1977), McCarthy and Donchin (1981), and Magliero et al. (1984) have been frequently quoted in the dual-task studies, because they were considered of crucial importance for making inferences from P3 amplitude in decomposing the processing requirements of complex tasks.

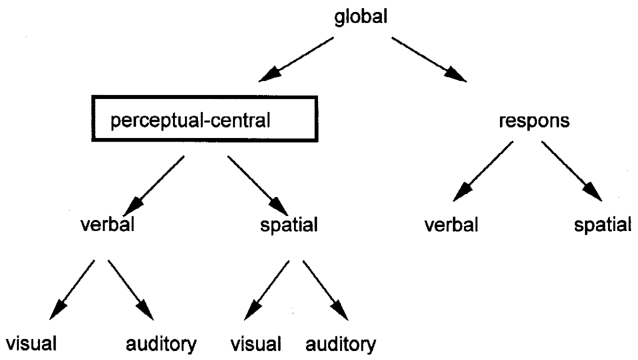

Figure 1. The hierarchical structure of Wickens' multiple resource model. Upper level: global resources, lower levels: increasingly differentiated resources (see text for further explanation). It was further proposed that demands upon perceptual-central resources are reflected in P3 amplitude.

It is not my intention to profoundly discuss the theoretical mechanisms that underlie interference in cognitive task performance and the question whether attentional resources are unitary or multiple. The main purpose of the present study is to critically examine results from a number of studies performed in the last two decades in which variations in amplitude of the P3 component of the ERP were related to task variables that were assumed to affect intensity or "load" of cognitive task operations. I shall examine in particular strong (and still prevalent) claims that P3 amplitude is selectively sensitive to resources of a perceptual/cognitive nature. P3 amplitude studies will be reviewed within a broad context of both single-task and dual-task studies, and results will be discussed against the background of three sets of different experimental variables, namely task difficulty, subjective control (also denoted as task priority or emphasis), and involuntary capture of attention. In view of their relevance for the interpretation of the relationship between P3 amplitude and processing capacity, I shall first briefly discuss each of these variables in the section below. The third section then provides an overview of some early hypotheses regarding the determinants of P3 amplitude and the fourth section describes the results of a review of the literature in which the relationship between P3 amplitude and cognitive task demands was investigated more systematically. Finally in the fifth section I shall discuss the utility of P3 amplitude as a measure of processing capacity and propose a model to integrate the major findings of my review.

FACTORS THAT DETERMINE CAPACITY DEMANDS

Task Difficulty

It has been assumed that the amount of resources or "effort" allocated to a task is determined by the intrinsic demands, also

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[2] There is considerable variation in the terminology used by researchers to designate resources underlying P3, even among researchers who share the same theoretical orientation. Some have used global terms like "attentional resources" (Johnson, 1988) or "extensiveness of controlled processing" (Rösler et al., 1986; Ullsperger & Neumann, 1986), whereas others (see, e.g., Donchin, 1981; Donchin & Isreal, 1980; Isreal, Chesney, et al., 1980; Kramer, Sirevaag, & Braune, 1987; Pritchard, 1981) use more specific terms like "perceptual resources," "perceptual-cognitive," or "perceptual/central resources."

denoted as task load or “difficulty” of the task (Kahneman, 1973; Navon & Gopher, 1980). Processing effort is assumed to be typically controlled by manipulations that change the task architecture, like the complexity of perceptual or memory-related processes.[3] Extensive practice reduces attentional demands of processes such as visual and memory search (Schneider & Shiffrin, 1977; Shiffrin & Schneider, 1977). Task difficulty and capacity are closely related concepts, as task difficulty determines the intensity or extent of resource demands (Wickens, 1987, 1991). This means that more effort needs to be invested to maintain a constant level of performance in a difficult task than in an easy task, which will usually lead to higher physiological costs.

Subjective Control

The amount of attention or capacity allocated to a task is not only determined by what a subject is doing, that is, the intrinsic demands of a task, but are also under subjective or intentional control (e.g., Mulder, 1986; Gopher, 1992; Gopher, Weil, & Siegel, 1989). Capacity allocation defined in terms of an intentionally controlled process has been investigated by using more stringent performance criteria, motivational incentives, or priority or emphasis instructions (Wickens, 1991). Note also that these task variables are sometimes also simply referred to as “task relevance.”

It is further worth emphasizing that in these conditions, the structural characteristics of the task conditions remain the same, and only instructions regarding the relative emphasis of different stimuli or tasks vary. In particular, research on focused and divided attention has provided a substantial amount of data demonstrating successful intentional control of processing capacity (e.g., Gopher, 1992; Mangun & Hillyard, 1990; Näätänen, 1992). In focused attention tasks, the subject is instructed to pay attention only to relevant stimuli with specific physical features and to ignore irrelevant stimuli. In dual task conditions, subjects must allocate the amount of attention to each of a set of qualitatively different tasks according to fixed proportions (e.g., ignore stimuli in task A and try to perform task B as well as possible, or try to perform both tasks as well as possible at the same time).

Involuntary Attention

Attention shifts may also be mediated by innate mechanisms that are tuned to events in the environment like novel, highly meaningful, or overlearned stimuli that seem to “capture” attention automatically (Graham & Hackley, 1991; Folk, Remington, & Johnston, 1992; Jonides, 1981; Kahneman, 1973; Theeuwes, 1994). These involuntary processes may sometimes even temporarily disrupt ongoing task performance when it is under voluntary control.

The pattern of physiological and behavioral responses elicited by novel or unpredictable stimuli is known as the orienting response (OR). ORs are innate involuntary attention responses that are elicited either by physical properties (e.g., intensity, duration) as well as semantic properties (meaning) of stimuli (Sokolov, 1963). One of the functions of the OR is allocation of capacity to “elaborate the stimulus” for further processing (Kahneman, 1973). This is manifested not only in larger ORs, but also in a prolongation in reaction time to novel or infrequent stimuli, as compared to familiar or frequent stimuli. Öhman (1979) has elaborated the orienting concept within an information-processing framework by proposing that the OR represents a “call” for further processing in a resource-limited system. The call may or may not be answered depending on whether the information-processing system is fully engaged in some other activity. Another feature of Öhman’s model was the assumption that ORs can be elicited either by low probability or novel stimuli, that produce a “mismatch,” or by highly meaningful, task-relevant stimuli that produce “matches” with internal representations.

DETERMINANTS OF P3 AMPLITUDE: SOME EARLY OBSERVATIONS AND HYPOTHESES

There is a close correspondence between the task variables that are assumed to determine demands on processing capacity and the “antecedent conditions” of P3 amplitude as described in early studies of P3. The majority of studies in which these conditions were established used relatively simple oddball tasks. They will be briefly listed below.

Task Relevance and Stimulus Probability

Two important determinants of P3 amplitude are task relevance and subjective probability (Donchin, 1981; Duncan-Johnson & Donchin, 1977, 1982; Pritchard, 1981; Squires, Donchin, Herning, & McCarthy, 1977). Task relevance is usually defined as the amount of attention that is paid to the stimulus (e.g., counting stimuli versus ignoring the same stimuli while reading a book). Subjective probability is manipulated by presenting unpredictable low probability stimuli that usually have “target” quality, that is, require a overt response (e.g., button press) or a covert response (e.g., mental count) by the subject, against a background of standard stimuli. An important observation of many studies has been that stimulus probability and task relevance interact with another. For instance, effects of stimulus probability on P3 amplitude are absent when subjects were actively ignoring these stimuli. This was accomplished (a) by giving them an unrelated task to perform (Duncan-Johnson & Donchin, 1977; Squires et al., 1975) or (b) by asking them to attend to other rapidly presented “relevant” stimuli embedded in the same task (Hillyard, 1981; Hillyard & Kutas, 1983).

The major interest in P3 amplitude as a reflection of processing capacity, however, stems not from its dependency on stimulus probability, but rather from its dependency on task relevance: A classical finding of early studies was that the amplitude of P3 became strongly reduced when a subject’s attention was directed away from the task in which the eliciting stimuli were embedded (Duncan-Johnson & Donchin, 1977; Johnson, 1988). A central question in subsequent studies (to be reviewed in the next section) was if P3 amplitude would also reflect more graded changes in attention as a function of different amounts of task priority (Donchin et al., 1986; Kramer & Spinks, 1991; Wickens, 1987).

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[3] Task difficulty is an ill-defined concept (see Kantowitz, 1987). Navon and Gopher (1980) have argued that task difficulty is determined both by the level of intended performance (e.g., tolerance for error) and the “subject-task parameters”: the constraints imposed on the information processing system by the task and the state of the subject (e.g., amount of practice, specific abilities). In the present paper, task difficulty is conceptualized in a strictly operational sense as the structural characteristics of a task that will increase the time required to perform the task or decrease the efficiency of task performance, given that the subject is optimally motivated to perform well. Some important determinants of task difficulty (in the latter definition) are task complexity or number of task operations or processing steps, level of practice, “data-limitation” (perceptual quality) and time pressure. Level of practice or “automaticity” is also considered to affect task architecture, because extended practice is believed to reduce the number of processing steps or task complexity (see also Shiffrin, Dumais, & Schneider, 1981).

Meaning

Another factor that could affect P3 amplitude is the “meaning” or “salience” of the stimulus. Stimuli with high emotional value, informative feed-back stimuli, and target stimuli usually elicit larger P3s than stimuli that do not have these properties (see Johnson, 1988, Picton, 1992, and Pritchard, 1981, for early reviews). Note also that in addition to variables like task relevance and subjective probability, stimulus meaning or salience has also been considered to be an important determinant of the orienting response (Pritchard, 1981; Sokolov, 1963).

Task Difficulty

The findings listed above suggest that when more attention is invested in a task or stimulus (either actively or passively), P3 amplitude will increase. However, when the effect of task difficulty on P3 amplitude is considered, the picture becomes more problematic. Although a higher level of task difficulty is assumed to mobilize more processing effort or resources, there is ample evidence suggesting that P3 amplitude decreases with task conditions that lower external or internal stimulus discriminability. On the basis of these findings, several authors in the past have suggested that P3 amplitude reflects the amount of information transmitted during presentation of a stimulus (Johnson, 1986, 1988; Kok, 1986, 1997; Parasuraman & Beatty, 1980; Ruchkin & Sutton, 1978; Scheffers & Johnson, 1994; Sutton, Braren, Zubin, & John, 1965; Sutton, Tueting, Zubin, & John, 1967). The amount of information is assumed to have an inverse relationship with the subject’s degree of “equivocation” or the post hoc uncertainty about having correctly perceived an event.

A REVIEW OF P3 STUDIES

Focus of the Review

In the present section, I shall further discuss the utility of P3 amplitude as a reflection of specific resource demands in the light of the resource framework outlined in the previous section (and depicted schematically in Figure 1). In reviewing the relevant P3 studies, special attention will be paid to the following three issues: (a) the different way task difficulty and attentional (i.e., priority) manipulations may affect P3 amplitude, (b) alternative interpretations of P3 amplitude in terms of equivocation and involuntary attentional responses in tasks that manipulated difficulty of cognitive operations, and (c) overlap between P3 and slow negative waves in complex paradigms that involved activation of working memory.

Criteria for Selecting ERP Studies

It is not the intention of the following review to provide an exhaustive survey of all studies that have reported P3 amplitude results in the settings of cognitive tasks. Rather, my purpose is to select a subset of the more substantial studies that were based on information processing models or experimental paradigms and that allowed quantitative inferences about the relationship between processing resources and P3 amplitude. The review also excludes research in areas that to my knowledge have provided no or only very marginal data on P3 amplitude, such as (a) studies on effects of mental effort to compensate for the detrimental effect of suboptimal states (e.g., noise, mental fatigue) on performance, (b) studies on effects of motivational incentives, (c) studies using irrelevant “probe” stimuli as a measure of spare capacity, and (d) studies that have used the noise-incompatibility paradigm (Eriksen & Eriksen, 1974).

P3 studies were selected according to the following criteria. First, only studies were selected that have used either difficulty or priority manipulations, as described in the second section. Because these task variables induce effortful, “controlled” processing, they seemed to be most relevant for clarifying the relationship between P3 amplitude and processing capacity. In this context, special attention will also be paid to (a) visual and memory search studies that have compared P3s in conditions of controlled and automatic processing and (b) conditions in which P3s could have been elicited automatically by attention capture. Second, only studies were selected that described effects of experimental manipulations on both performance measures and P3 amplitude. An increase in task difficulty was inferred from a prolongation of reaction time and/or increased error rate. In addition, a prolongation of P3 latency was taken as a sign that the processes that underlie P3 amplitude were also delayed in time.

Because results of both single-task and dual-task studies are relevant for making inferences from P3 amplitude with regard to capacity, my review will also pay attention to both types of studies.

Single-Task Studies

The following categories of single-task paradigms have been used in combination with ERP measures: focused-attention tasks, visual and memory-search tasks, complex perceptual/conceptual tasks, and choice-reaction tasks. Focused attention usually requires the focusing of a single relevant stimulus attribute, whereas visual and memory search, also sometimes referred to as “divided attention,” requires a division of attention between various stimuli on a display, or various items stored in memory. Both types of paradigms have been applied to activate early perceptual as well as late memory-dependent processes. Furthermore, a number of choice-reaction tasks have used task manipulations that enable the isolation of elementary processing components like encoding, response selection, and response execution. According to Sanders (1983) and Wickens (1984), processing stages also depend on energetical supply mechanisms. Thus, the latter studies could provide important information regarding the diagnostic value of P3 in distinguishing between resources demanded by these more elementary processing components (also see Table 1 for an overview).

Focused Attention Tasks

A consistent finding of focused attention studies that used fast stimulus presentation rates (ISIs varying between 400 and 800 ms) was that only the attended targets elicited a P3 component (Hillyard, 1981; Hillyard & Kutas, 1983; Hillyard, Picton, & Regan, 1978). Hillyard and coworkers further argued that attention-related negative waves and P3 reflect two different hierarchically ordered levels of processing: earlier selection potentials [reflected in N1 and the early portion of the “negative difference wave” (Nd)] represented processing related to “stimulus set,” whereas P3 was dependent on subjects’ “response set.” Response set, the mechanism supposed to be reflected by P3, was described as a selection mechanism that is based on a more detailed and higher level of processing, that is, when sensory information is compared against memorized templates or internal models.

A strictly hierarchical model predicts that the onset of early negativities (N1, Nd) and P3 are correlated with each other. However, according to Näätänen (1982, 1992), the available data in focused-attention tasks do not provide much support for this pre-

Table 1. *Summary of P3 Amplitude Findings in Single-Task Studies*

Task manipulations	Relevant studies	Major results
Focused attention	Hillyard & Kutas, 1983 a.o.; Hillyard et al., 1978; Looren de Jong et al., 1988; Lorist et al., 1994; Okita et al., 1985; van der Stelt et al., 1998	Larger P3 to attended than unattended targets
Focus versus divided attention	Mangun & Hillyard, 1990	Larger P3s to target stimuli in focused than divided condition
Visual search: memory load	Brookhuis et al., 1981; Gomer et al., 1976; Gunter et al., 1992; Kotchoubey et al., 1996; Kramer et al., 1986; Looren de Jong et al., 1988; Lorist et al., 1994, 1996; Mecklinger et al., 1992; Okita et al., 1985; Pelosi et al., 1995; Strayer & Kramer, 1990; Wijers et al., 1989a,b	Smaller P3 with greater memory load
Visual search: display load	Brookhuis et al., 1981; Hoffman et al., 1983; Kok et al., 1987; Lorist et al., 1996; Smid et al., 1991;* van Dellen et al., 1985; Wijers et al., 1987; Zeef & Kok, 1992a	Smaller P3 with greater perceptual load
	Luck & Hillyard, 1990	Larger P3s with greater perceptual load and lower subjective probability of targets
Visual search: automatic versus controlled processing	Hoffman et al., 1983; Kramer et al., 1986; van Dellen et al., 1985	Larger (or equal amplitude) P3s in consistent relative to varied mapping conditions
Complex perceptual and/or conceptual operations	García-Larrea & Cézanne-Bert, 1998; Wijers et al., 1989a	Smaller P3 with greater perceptual load
	Ullsperger & Neumann, 1986; Ullsperger et al., 1988	Larger P3 with greater complexity of matching operations
Elementary processing stages: stimulus quality	Ford et al., 1982; McCarthy & Donchin, 1981; Pfefferbaum et al., 1983, 1985; Smulders et al., 1995	P3 amplitude equal for degraded and intact stimuli (single-trial P3s)
	Christensen et al., 1996; Magliero et al., 1984;* Pfefferbaum et al., 1986; Pfefferbaum & Ford, 1988	Smaller P3s for degraded than intact stimuli (single-trial P3s)
	Kok, 1986; Kok & Looren de Jong, 1980a; Kok et al., 1985; Lorist et al., 1994; Ruchkin et al., 1988; Scheffers et al., 1991	Same result as above (average P3s)
Elementary processing stages: response compatibility	Ragot, 1984; Ragot & Renault, 1981	Amplitude P3s not different in incompatible and compatible conditions
	Christensen et al., 1996; Magliero et al., 1984;* McCarthy & Donchin, 1981;* Pfefferbaum et al., 1986	Smaller P3s in incompatible than compatible conditions
	Ragot & Fiori, 1994	Larger P3s in incompatible than compatible conditions
Elementary processing stages: response complexity	Ragot, 1984; Ragot & Renault, 1981	No effect on P3 amplitude
	Smulders et al., 1995*	Smaller P3s in complex than in simple conditions

*Result based upon visual inspection.

diction. First, the differential P3 effect is almost immediately present in the beginning of the experiment, whereas the N1 effect takes some time to develop. Second, it has been shown that "channel separation" (i.e., the physical disparity between relevant and irrelevant stimuli) affects Nd amplitude but not P3 amplitude or latency (Hansen & Hillyard, 1983). A later study by Mangun & Hillyard (1990; see further below) demonstrated that in visual attention tasks, higher processing stages reflected in P3 amplitude do not necessarily depend on stages reflected in early ERP components. Thus, these findings support the view that in tasks requiring selective focusing of attention, sensory and central-cognitive processes do not always have to follow each other in a strictly serial or hierarchical order, and can operate in a more or less independent fashion.

Some studies have used the focused attention paradigm in combination with lower presentation rates of relevant and irrelevant visual stimuli (ISIs of approximately 1–2 s). A first finding in these studies was that attended nontarget stimuli also elicited substantial P3s, albeit of a lower amplitude than attended-target stimuli, at corresponding levels of a priori probability (Looren de

Jong, Kok, & van Rooy, 1988; Lorist, Snel, Kok, & Mulder, 1994; van der Stelt, Kok, Smulders, Snel, & Gunning, 1998). In contrast with studies that have used fast presentation rates, these studies also reported a late positive deflection for target stimuli presented at the irrelevant channel (Looren de Jong et al., 1988; Lorist et al., 1994; Okita, Wijers, Mulder, & Mulder, 1985; van der Stelt et al., 1998). The fact that this component was more centrally distributed at the scalp, suggests that it could also represent the P3a component, a component that is assumed to be functionally separable from the classical centroparietal P3(b) (Squires et al., 1975).

The latter findings support the view that in visual selective attention paradigms that use a relatively low presentation rate of stimuli, processing of irrelevant information cannot be always suppressed (Lavie, 1995; Lavie & Tsal, 1994). In contrast with high load filtering paradigms, the paradigms used in these P3 studies can be considered as typical representatives of "selective set paradigms" that have used a much lower perceptual load (Kahneman & Treisman, 1984).

Focused Versus Divided Attention

In the tasks described above, subjects were instructed to attend to relevant stimuli and not to pay attention to the irrelevant stimuli. In other studies, the relative allocation of attention to stimulus features was varied in a more gradual fashion (e.g., pay 50% attention to stimuli presented in the right visual field and 50% attention to stimuli in the left visual field, as compared with 100% attention to the right field and 0% attention to the left field). Although these studies may be considered as a special case of dual-task studies (reviewed further below in this paper), I prefer to discuss them in the present section, because their results seems to be a logical extension of those of the focused-attention studies.

Most of these studies described results only for the early negative going component (N1) of the ERP. The major finding was that the amplitude of N1 in the divided attention condition was intermediate between those elicited by the attended and unattended channels during focused attention (Hink, van Voorhis, & Hillyard, 1977; Parasuraman, 1978, 1990; Van Voorhis & Hillyard, 1977; but see also Kok, 1997 for a more detailed review). Of particular relevance for the present review is a study by Mangun & Hillyard (1990). They systematically varied the priority of visuospatial attention in a task in which subjects were required to react to letter patterns that were presented randomly and at a high rate in the left and right visual fields. Subjects were instructed to focus attention exclusively on either left or right field stimuli, or divide their attention in different proportions between the fields. Both N1/P1 and P3 results were analyzed. It was found that P1 and N1 amplitudes progressively increased with greater attentional allocation to the eliciting stimuli. The attentional operating characteristic (AOC) functions of these components (amplitudes of components plotted separately for left and right field stimuli as a function of task priority; see Sperling, 1984) showed a steep almost linear amplitude trade-off as attention was increasingly allocated to one visual field at the expense of the other. With respect to P3 amplitude to target stimuli, the AOC curves showed a more rectangular form that was similar to that observed for the performance measures. The authors suggested that reductions in earlier selection processes (reflected in P1 and N1 amplitudes) need not be paralleled by proportional reductions in detection performance and the associated P3 component. Apparently, they concluded, the higher processing stages reflected by P3 could still achieve accurate identification of the target quality despite the lower level of sensory gain.

Visual and Memory Search

In visual search tasks, subjects must detect targets on a display that contains a number of nontarget stimuli or "distractors" that are presented simultaneously with the target (the "display set"). A specific hybrid version of a visual search was developed by Shiffrin and Schneider in which the number of target stimuli or "memory set" was also varied (Schneider & Shiffrin, 1977; Schneider, Dumais, & Shiffrin, 1984; Shiffrin & Schneider, 1977). The advantage of this approach is that it allows examination of effects of difficulty of both perceptual and memory-dependent processes on P3 amplitude: Perceptual load is manipulated by varying the display set, whereas memory load is manipulated by varying the memory set. The classical Sternberg task (Sternberg, 1969) may be seen as a special version of a visual search task, in which only the memory load is varied and the display load is minimal: The display contains only one stimulus, a target or a nontarget. Although other varieties of visual search tasks have been described in recent literature based on different conceptual frameworks, the present review will be restricted to the older paradigms, because they have been used most frequently in combination with P3 measures.

Effects of Memory Load

A classical finding of many visual search studies using alphanumeric stimuli was that the slope of the memory load function was much steeper for reaction time than for P3 latency (Brookhuis et al., 1981; Ford et al., 1979; Ford, Pfefferbaum, Tinklenberg, & Kopell, 1982; Gomer, Spicuzza, & O'Donnell, 1976; Kramer & Strayer, 1988; Mecklinger, Kramer, & Strayer, 1992; Pelosi, Hayward, & Blumhardt, 1995; Rösler et al., 1986; Zeef, Kok, & Kenemans, 2001; see also Verleger, 1997 for a general review). These results could indicate that P3 is less sensitive than performance measures, and might saturate earlier when demands are high (see also Meyer, Osman, Irwin, & Yantis, 1988). The prevailing interpretation of the P3/reaction time dissociation however is that memory load affects not only the memory comparison process (presumed to be reflected in P3 latency) but also response related stages that follow the memory comparison and the subsequent binary decision stages. For instance, Ford et al. suggested that a reason why reaction time was more delayed than P3 latency during high memory load could be that subjects followed a more cautious response strategy in the high load than in the low load conditions (Ford, Mohs, Pfefferbaum, & Kopell, 1980).

With respect to P3 amplitude the majority of studies using alphanumerical stimuli have reported that P3 amplitude decreases as a function of increase of the memory set (Brookhuis et al., 1981; Gomer et al., 1976; Gunter, Jackson, & Mulder, 1992; Kotchoubey, Jordan, Grözinger, & Westphal, 1996; Kramer, Schneider, Fisk, & Donchin, 1986; Looren de Jong et al., 1988; Lorist et al., 1994; Lorist, Snel, Kok, & Mulder, 1996; Mecklinger et al., 1992; Okita et al., 1985; Pelosi et al., 1995; Strayer & Kramer, 1990; Wijers, Mulder, Okita, & Mulder, 1989; Wijers, Otten, Feenstra, Mulder, & Mulder, 1989). These results were obtained in "varied-mapping" (VM) conditions, that is, when stimulus-response associations were varied constantly over trials or over subblocks of trials.

In interpreting these results, the following five factors could have contributed to the reduction of P3 amplitude with increasing memory load (see also Kok, 1997).

Latency jitter. Smaller P3s could have resulted from a larger variability ("jitter") of P3 across individual trials in the high than in the low memory load conditions. However, the fact that some of the prior studies also found a P3 reduction with high memory load when P3 amplitude was measured on a single-trial basis (e.g., Brookhuis et al., 1981; Gunter et al., 1992; Kramer et al., 1986; Mecklinger et al., 1992) indicates that latency jitter cannot be the sole factor that is responsible for the reduction of P3 amplitude in high load conditions.

Equivocation. Amplitude reduction of P3 in high memory load could have reflected stronger equivocation or the subjects' decreased confidence about having perceived the correct target event. In memory search tasks, equivocation could have resulted from weaker memory representations or lower internal discriminability of target events (Johnson, 1988; Johnson & Donchin, 1985; Ruchkin & Sutton, 1978).

Overlap between multiple P3s. Some authors have suggested that effects of cognitive task manipulations on the latency, amplitude, or topography of P3 are distorted due to overlap between P3a and P3b (Brookhuis et al., 1981) or between two successive subcomponents of the P3b complex (Falkenstein, Hohnsbein, & Hoormann, 1994; Falkenstein, Koshlykova, Kiroj, Hoormann, & Hohnsbein, 1995). The common aspect of their arguments is that when task conditions become more difficult (as in high load conditions of the memory search task), the second peak shifts in time, whereas the first peak remains relatively stable. Thus, in the easy condition, the two components add, whereas in the more difficult conditions, the mutual enhancement diminishes, which in turn leads to a reduction in P3 amplitude.

Overlap P3 with slow negative waves. A different type of overlap was suggested by Wijers (Wijers et al., 1989b, but see also Okita et al., 1985, and Pelosi et al., 1995). They proposed that the P3 reduction effect in memory search tasks was due to overlap between P3 and a sustained negative wave (that they labeled "search negativity") that occurred in the same latency range as P3.[4] The negative waves were computed by subtracting ERPs to nontarget stimuli in low memory conditions from ERPs to nontarget stimuli in the high memory load conditions. According to Wijers et al. (1989) the search negativities reflect controlled search processes and are functionally related to the processing negativities found in auditory focused attention tasks (Näätänen, 1992). Pelosi et al. (1995) further suggested on the basis of inspection of individual waveforms that the negative amplitude shift overlapping with the P3 complex could also cause an artificial (apparent) group latency shift of P3 in the high load conditions.

These results raise the question to what extent the P3 reduction in search tasks is "nothing but" an artifact caused by overlap with sustained negative waves. There is evidence suggesting that this is not the case. For instance, Kramer et al. (1986) and Mecklinger et al. (1992) have demonstrated by using principal component analysis (PCA) of ERP waveforms that P3 and negative slow wave activity could be clearly dissociated both by their scalp distribution and sensitivity to memory load. PCA factors scores were sensitive in a reciprocal fashion to variations in memory load: P3 positivity decreased at Pz whereas slow wave negativity increased at Cz with increasing set size. Thus, a more plausible conclusion is that in the previous studies, P3 reduction with increased size of the memory set reflected various simultaneous influences.

Resource reallocation. A final interpretation has been proposed by Kramer and colleagues (Kramer et al., 1986; Strayer & Kramer, 1990). They suggested that the decrease in P3 amplitude was due to the complex multicomponent nature of the memory search task, in which resources demanded by the probe comparison (or serial comparison) process are "re-allocated" or depleted by the memory rehearsal component of the search task (Figure 2, left). Memory rehearsal was conceived of as a spontaneous ongoing activity that is not time-locked with the target identification or serial comparison process. Thus, increasing memory load gradually leads to the availability of fewer resources, thereby decreasing the amplitude of P3 to the target stimuli in the search task. Note that the latter interpretation of P3 follows directly from Wickens' resource model (Figure 1), which assumes that working-memory processes ("codes of processing") also make demands on perceptual-central resources. Figure 2 (right) also shows an alternative interpretation of resource reallocation suggested by Kok (1997). According to the latter view, P3 amplitude only reflects resources invested in the target identification process and smaller P3s with higher memory load result from depletion of resources by the serial comparison process and overlap with negative slow waves.

Effects of Perceptual Load

A number of visual search studies have demonstrated that varying the display set and the memory set have identical effects on reaction time, which suggests that both task operations are equally effective in manipulating control processes (Schneider et al., 1984). ERP studies that varied display load (alphanumeric stimuli) have also reported a delay of P3 latency, and a reduction of P3 amplitude with an increase of the display load (Brookhuis et al., 1981; Hoffman, Simons, & Houck, 1983; Kok, Looren de Jong, Woestenburg, Logman, & Rooy, 1987; Lorist et al., 1996; Smid, Lamain, Hogeboom, Mulder, & Mulder, 1991; van Dellen, Brookhuis, Mulder, Okita, & Mulder, 1985; Wijers et al., 1987; Zeef & Kok, 1992a). Brookhuis et al. (1981) measured P3s on the basis of a single-trial adaptive averaging technique that precludes an interpretation of their P3 amplitude reduction effect in terms of an increased latency variability. However in the Hoffman et al. (1983) study, the P3 reduction effect disappeared after correction for latency variability. Furthermore, some of these studies reported that the decrease in P3 amplitude as a function of display load appeared to be more prominent at the posterior (Pz) scalp site, whereas effects of memory load on P3 amplitude had a more central (Cz) focus at the scalp (Lorist et al., 1996; Wijers et al., 1987; Zeef & Kok, 1992a).

Deviating results were found by Luck and Hillyard (1990) in a visual search task with abstract stimuli (triangles with or without additional features). They also reported longer reaction times and

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[4] The overlap issue seems to be especially relevant in multicomponent (e.g., memory search) tasks in conditions when P3 and slow negative waves are active in the same time range. Wijers (1989, p. 238) have discussed the various possibilities that exist in this kind of paradigm. When controlled search processes and target detection occur in a strictly sequential fashion, then one would expect little temporal overlap between search-related negativity and P3. However, substantial overlap could occur when the mental processes do overlap in time, for example, when the search process continues after the target detection process has finished. A second type of source of ERP overlap could originate not from mental processes, but from the neural activities underlying these processes. For instance, it is imaginable that neural activity during memory search persists sometime after the mental processes have already terminated (see also Meyer et al., 1988, for a discussion of the same problem). Finally, another cause of more artificial ERP overlap could result from the fact that the processes that generate these components have a variable latency and duration across single trials, and are smeared out in time in the averaging process. In this case, slow negative shifts and P3 could show overlap although the underlying processes do not overlap.

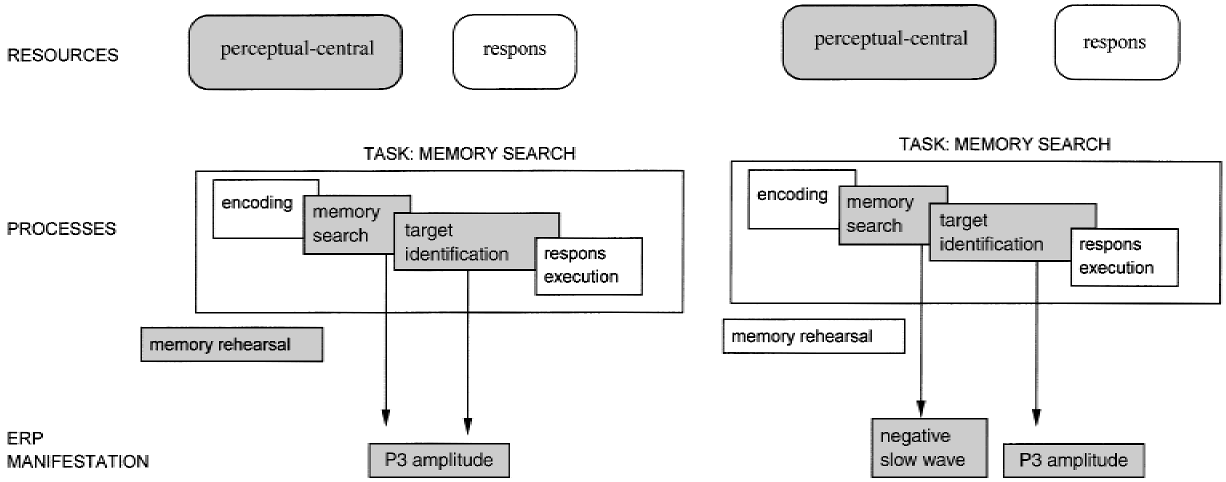

Figure 2. Left: Representation of the resource-reallocation principle proposed by Kramer to account for the reduction of P3 amplitude with increasing memory load. Dark areas represent resources, related processes, and ERP components supposed to be affected by memory-load manipulations. P3 amplitude reflects demands on the same pool of perceptual-central resources depleted by both target identification and memory search processes. Memory rehearsal is conceived of as a process that is not time-locked with memory search processes, but still makes demands on perceptual-central resources. Thus, a consequence of increasing memory load is that less resources are available for the memory search and target identification processes due to increasing demands of memory rehearsal. Right: Alternative view proposed by Kok (1997), in which P3 amplitude is assumed to reflect only resources invested in target identification. Here, the smaller P3 with greater load is attributable to two factors, namely (a) resources depleted (reallocated) by the memory search process and (b) overlap with negative slow wave.

P3 latencies with increasing set size of the display. In contrast with the prior results, P3 amplitude of response locked ERPs showed an increase with size, but only when feature-absent stimuli were targets. Note that in almost all the other visual search studies cited above, effects of display or memory load on P3 amplitude were of almost the same magnitude for target and nontarget trials. This could indicate that in the present study, P3 enhancement with increasing set size reflected other more specific aspects of processing than demands on a limited capacity system. One possibility that was also suggested by the authors is that the P3 enhancement with greater set size reflected the lower subjective probability of targets in these conditions. Because in the present study both the paradigm (type of stimuli, interstimulus interval) and scoring method of P3 (response locked averaging) deviated in several respects from those used in other search studies, the results are difficult to interpret in the context of the prevailing model of effortful controlled processes of Shiffrin and Schneider (1977).

Automatic Versus Controlled Processing

The visual search paradigm has also been used extensively to study controlled and automatic processing. Controlled processing is assumed to play a role in situations in which stimulus–response relations are varied over time. Shiffrin and Schneider have labeled these conditions as varied mapping (VM) conditions: targets and nontargets constantly change roles over successive trials. In addition, automatic detection develops during consistent mapping (CM), that is, when targets and nontargets never change roles over trials. Extensive practice reduces demands of controlled processing in visual search tasks, at least in CM conditions when the stimulus–response associations are unaltered (Schneider et al., 1984).

The studies reported above demonstrated that larger P3s are elicited by stimuli in low than in high memory load conditions. Therefore it seems plausible that development of automatic processing, and the concomitant reduction of demands on limited capacity, should lead to enhancement of P3 amplitude. Indeed, the available evidence seems to globally confirm this hypothesis.

An early study by Hoffman demonstrated that P3s that were elicited by stimuli in consistent mapping conditions were earlier and of almost the same magnitude as P3s elicited by stimuli in varied mapping conditions, even after latency adjustment of P3s (Hoffman et al., 1983). Furthermore, the effects of display size on reaction time and P3 latency were much smaller in consistent than varied mapping conditions. Even more convincing are the results of two other studies that reported an increase of P3 amplitude as a function of practice (Kramer et al., 1986; van Dellen et al., 1985). After extensive training, P3s to high probability CM stimuli became even significantly larger than those to VM stimuli (Kramer et al., 1986). Consistent with the study of Hoffman, Kramer further showed that effects of memory load on P3 amplitude were much smaller during the consistent mapping than during the varied mapping condition. The effects of memory set size on P3 latency and reaction time also became reduced with practice, but mostly in the consistent mapping condition. Similar P3 latency/reaction time results were obtained a subsequent study by Kramer and Strayer (1988).

Intentional Control Versus Difficulty of Search Operations

The studies described in the previous sections were mainly concerned with the question how P3 amplitude is affected by the complexity of search operations. To my knowledge, only one ERP study has systematically addressed the issue of to what extent search operations and their ERP manifestations are affected by intentional (i.e., voluntary) control. Zeef, Kok, and Kenemans (2001) manipulated the difficulty of search operations by varying the number of nontarget stimuli on the display (display load) and the size of the memory set (memory load). In a separate condition, subjects performed the same task but also received a feedback stimulus after each trial. Feedback consisted of a red or green light informing subjects about the speed and accuracy of their response relative to an individually determined criterion value. Feedback resulted in faster and slightly less accurate responses relative to the condition without feedback. Interestingly, feedback resulted in a slight increase of P3s to target stimuli, and concomitant decrease and earlier termination of the search-related negativity (difference waves ERPs low minus high load conditions) relative to no feedback. Thus it appeared from these findings that intentional control and task difficulty had contrasting effects on the ERP components that were elicited by the search processes.

Tasks Using Other Complex Perceptual and Conceptual Operations

A number of ERP studies have used a variety of complex conceptual operations such as mental rotation, concept formation, arithmetic, and semantic processing. The paradigms used in these studies usually elicited prolonged slow negative waves that often extended the typical P3 latency range (i.e., 300–600 ms). Most authors interpreted these negative waves as signs of continued processing in working memory (e.g., Lang et al., 1987; McCallum, Cooper, & Pocock, 1988; Peronnet & Farah, 1989; Rösler, Heil, & Röder, 1997; Ruchkin, Canoune, Johnson, & Ritter, 1995; Ruchkin, Johnson, Mahaffey, & Sutton, 1988; Wijers et al., 1989a). For the sake of brevity, I shall restrict my review of these studies to those papers that also reported the effect of task manipulations on P3 amplitude.

Wijers et al. (1989a) used a Sternberg memory scanning tasks in which the probe (target or nontarget) stimuli were rotated letters. The effect of mental rotation (i.e., the angle of rotation) became apparent as a systematic reduction in amplitude of P3 to target stimuli, which was most prominent at the posterior (Pz) site. P3 reduction was ascribed to overlapping negative shift that was active in the same time frame as P3.

Finally, a study by García-Larrea & Cézanne-Bert (1998) found that P3 amplitude systematically decreased in amplitude with the subjective difficulty of target identification in an auditory oddball task. The difficulty of the task was manipulated by requiring the subjects to perform complex subsidiary mental operations like counting (forward and backward) and transformation of semantic information. They further reported that a slow positive wave emerged in the more difficult conditions. These results are reminiscent of earlier findings of Ruchkin (Ruchkin & Sutton, 1983; Ruchkin et al., 1988), who also concluded that positive slow waves with a centroparietal distributions were elicited by target stimuli in difficult perceptual discrimination tasks.

It should be noted that in these studies, ERP components were measured on the basis of averaged ERP waveforms. Single-trial scoring or filtering techniques that are customary for measurement of P3 are not applicable for these more sustained potential shifts. Therefore it cannot be ruled out that reduction of P3 amplitude was also influenced by greater latency variability of P3 in the more difficult conditions.

Two studies, however, reported results that deviated from the general pattern of the prior studies. Ullsperger, Metz, and Gille (1988) did not observe an effect of complexity of linguistic or mathematical operations on either sustained negative waves or P3 amplitude. They used a matching task in which subjects had to match either two sequences of nonsense syllables (Experiment 1) or two sequences of digits (Experiment 2) that were presented simultaneously on a screen. The difficulty of the matching operation was varied systematically by applying linguistic or mathematical rules of increasing complexity. Although the more difficult categories elicited longer reaction times and more errors, P3 amplitude remained equal or even increased slightly with greater task difficulty. Similar results were reported in an earlier study by Ullsperger (Ullsperger & Neumann, 1986) in which they used the same type of paradigm, but varied the perceptual difficulty of the matching operation. In this study, P3 amplitude also seemed to increase with greater task difficulty.

It is hard to tell which factors were responsible for the deviant pattern of results in the latter two studies. One possibility is that, because the investigators were primarily interested in the P3 component, they could have overlooked more sustained potentials shifts in their ERP waveforms. Another factor that could have especially played a role in the study of Ullsperger and Neumann (1986), is that stimuli in the more difficult conditions had a greater complexity or “signal value.” Thus, stronger orienting to these stimuli could have been partly responsible for the larger P3s that were found in the more difficult conditions.

Tasks That Manipulated the Difficulty of Elementary Processing Stages

In this section, the effects of three different task variables, stimulus quality, stimulus–response compatibility, and response complexity, on P3 amplitude will be discussed. According to the framework of the additive factors method (see Sanders, 1997; Sternberg, 1969), these variables will affect the following stages: feature analysis (or encoding), response selection, and response execution. Following the cognitive-energetical model of Sanders (1983), an effect of one these variables on P3 amplitude will be taken as a sign that the related processing stage has also made demands on a specific (perceptual, central, or response) resource system. Note that memory set size that is presumed to affect the memory comparison stage (Sternberg, 1969) will be left out of consideration, because this task variable has already been discussed extensively in the section “Visual and Memory Search.”

Stimulus Quality

Many studies have demonstrated that visual stimulus degradation, a task manipulation that affects the encoding stage, causes an increase in reaction time and a decrease in accuracy of responding. Some of the ERP studies that have used the same manipulation reported a delay in P3 latency, but found no effects on P3 amplitude (Ford et al., 1982; McCarthy & Donchin, 1981; Pfefferbaum, Ford, Johnson, Wenegrat, & Kopell, 1983; Pfefferbaum, Ford, Weller, & Kopell, 1985; Smulders et al., 1995). Finally, Christensen, Ford, and Pfefferbaum (1996), Magliero et al. (1984), Pfefferbaum and Ford (1988), and Pfefferbaum, Christensen, Ford, and Kopell (1986) reported both an increase in P3 latency and a decrease of P3 amplitude with stimulus degradation. With the exception of the study by Smulders et al. (1995), all these studies measured P3 on the basis of latency-adjusted averages.

In contrast, a number of studies reported that degradation of visual stimuli caused a reduction of P3 amplitude, but had only small and nonsignificant effects on P3 latency (Kok, 1986; Kok & Looren de Jong, 1980a; Kok, van de Vijver, & Rooyakkers, 1985; Lorist et al., 1994; Ruchkin et al., 1988; Scheffers, Johnson, & Ruchkin, 1991). In these studies, however, P3 was measured on the basis of the average ERP waveforms. Thus it is probable that smaller P3s were partly due to a greater latency jitter of P3 in the more difficult discrimination conditions. In the same studies, latency jitter could perhaps also have masked a latency difference between easy and difficult discrimination conditions.

Some studies that varied perceptual difficulty of visual stimuli also reported effects on a late positive ERP component that was labeled positive slow wave (Cremer, Kok, Zeef, & Keuss, 1996; Kok, 1986; Kok & Looren de Jong, 1980a; Kok et al., 1985; Ruchkin & Sutton, 1983; Ruchkin, Sutton, Kietzman, & Silver, 1980; Squires et al., 1975). Gunter, Jackson, and Mulder (1995) and Ruchkin et al. (1988) suggested that in contrast with slow negative waves that reflected difficulty of conceptual operations, positive slow waves reflected difficulty of perceptual operations and memory storage. Another suggestion was that slow positive waves are functionally closely related to P3 and represent "continued processing" in situations when perception is made difficult, as in signal detection or recognition paradigms (Kok & Looren de Jong, 1980a; Ruchkin et al., 1980).

Note however that the issue of whether slow positive waves are a functionally distinct ERP component or represent a "smeared out" and delayed P3 has not yet been definitely settled (Johnson & Donchin, 1985; Johnson, 1988).

Stimulus-Response Compatibility

Unfortunately, only a few ERP studies that manipulated stimulus–response compatibility have reported effects on P3 amplitude. Two versions of stimulus–response compatibility have been used in these studies; semantic and spatial incompatibility. Christensen et al. (1996), McCarthy & Donchin, 1981, Magliero et al. (1984), and Pfefferbaum et al. (1986) required subjects to react with the right and left hands when seeing the words LEFT and RIGHT, respectively. They reported significantly longer P3 latencies and reaction times, and smaller P3s to incompatible than compatible words for latency adjusted single trial P3s. Ragot and Fiori (1994), who used the same type of paradigm, reported slower reactions, but larger and later P3s to incompatible than compatible stimuli. The enlarged P3 was ascribed to the higher meaningfulness of the incompatible stimuli. Note, however, that they found two successive P3 peaks, and that the compatibility effect was only present for the second (late) P3 peak. Thus, the prolongation of P3 latency to incompatible stimuli could also have been an apparent latency shift caused by the amplitude increase of the second P3 component.

In two earlier studies by Ragot (Ragot, 1984; Ragot & Renault 1981), no effects of spatial incompatibility (i.e., requiring left/right hand reactions to visual stimuli presented at right and left locations on the screen, respectively) on P3 amplitude were found, and incompatible stimuli elicited slower reactions and longer P3 latencies than compatible stimuli.

Response Complexity

To my knowledge, only two studies have varied response complexity and also described the effects of this manipulation on P3 amplitude. In the two compatibility studies mentioned earlier, Ragot and Renault (1981) and Ragot (1984) asked subjects to react to the stimuli in conditions when hands were either crossed or uncrossed. Although this manipulation significantly increased reaction time, no effects were found on either the latency or amplitude of P3. Finally, Smulders et al. (1995) compared P3s to letter stimuli in a simple button-press response condition (response with index finger) with a more complex sequential finger response condition (three fingers beginning with the index finger). Although only effects of response complexity on reaction time and latency of P3 were submitted to statistical analysis, visual inspection of their P3 waveforms (their Figure 2) suggests that for response-locked ERPs, trials with complex movements elicited somewhat smaller P3s than trials with simple movements.

Dual-Task Studies

In dual-tasks experiments, subjects must perform simultaneously two qualitatively different tasks that are designated primary and secondary tasks. The rationale underlying this approach is that an increase in difficulty or priority of the primary task will lead to a decrease of resources available for the secondary task. It has sometimes been argued that in single-task conditions like Sternberg tasks, processing capacity is not fully occupied and that subjects can therefore easily "waste" resources on irrelevant stimuli. In dual-task situations, this is less likely to occur, because spare capacity is fully absorbed by the secondary task. The dual-task studies that also looked at P3 amplitude will be reported below (Table 2 summarizes the major findings obtained in two different paradigms, namely difficulty manipulation and priority manipulation.)

Difficulty Manipulations

The studies reported here all have in common that they were designed to mimic aspects of real-life dynamic operator environments, like flight control. Wickens used a visual tracking task as the primary task, in which subjects manipulated a control stick to keep a randomly moving cursor on the display centered with a circular target (Wickens, Isreal & Donchin, 1977). Difficulty of the primary task was manipulated by varying the number of dimensions in which the subject was required to track. In the easy (one-dimensional) condition, the cursor moved only to the left and right on a horizontal axis. In the difficult (two-dimensional) condition the cursor could move in any direction on the screen.

P3 amplitude was measured in an auditory oddball task in which subjects counted the deviant stimuli, which served as the secondary task. Although the P3 in the secondary task decreased in amplitude in the dual task relative to the single task oddball P3, it did not show a further amplitude decrease when difficulty of the primary task increased. Note that the latter effect could have simply reflected "costs of concurrence," and is therefore difficult to relate to specific processing demands of the primary task (Norman & Bobrow, 1975). A subsequent study by Isreal, Chesney et al. (1980) also failed to find an effect of primary task difficulty on P3 amplitude in a secondary task. They used the one-dimensional version of the same compensatory tracking task, but varied the bandwidth of the forcing function, that is, the equation that controls the velocity and frequency of directional reversals of the movement of the cursor on the screen.

In contrast to P3 amplitude that seemed to be insensitive to demands on resources induced by the primary task manipulations, both these studies found that reaction times in the oddball tasks increased systematically with an increase in tracking difficulty. A similar pattern of results later was found by Kramer and Strayer (1988), who also reported a performance trade-off in the absence of a trade-off in P3 amplitude in a study in which a step-tracking task was paired with a memory search task.

Three other visual tracking studies, however, did report a graded effect of primary task difficulty on the amplitude of P3 in the secondary oddball task. Isreal, Wickens, et al. (1980) varied the difficulty of a primary task by instructing the subject to monitor either four or eight display elements and to detect a change in course of the target by pressing a button. The authors concluded that the P3 decrement could not have resulted from greater latency jitter, because the decrease in amplitude was also observed in single-trial P3s. In a subsequent study by Kramer, Wickens & Donchin (1983), subjects covertly counted either auditory probes

Table 2. *Summary of P3 Amplitude Findings in Dual-Task Studies*

Task manipulations	Relevant studies	Major results
Difficulty manipulation (P3 measured only in secondary task)		
Number of tracking dimensions in primary task (one- versus two-dimensional tracking of constant moving cursor)	Wickens et al., 1977	No effect of tracking difficulty on P3 amplitude in secondary task (covert counting auditory targets)
Bandwidth of forcing function (one-dimensional tracking)	Isreal, Chesney, et al., 1980	Same result as above
Tracking course change of four versus eight display elements	Isreal, Wickens, et al., 1980	Decrease P3 amplitude in secondary task (button press to auditory targets) with greater difficulty of tracking
System order (first- versus second-order dynamics)	Kramer et al., 1983	Decrease P3 amplitude in secondary task
Number of tracking dimensions (acquisition versus alignment phase)		No decrease of P3 amplitude in secondary task (covert counting deviant visual probes embedded in primary task or auditory probes) with greater difficulty of tracking
Simulated flight scenario (easy versus difficult mission)	Kramer et al., 1987	Decrease P3 amplitude in secondary task (button press to auditory targets) with greater difficulty of tracking
Primary task: system order (step tracking)	Kramer & Strayer, 1988	No effect of tracking difficulty on P3 amplitude in visual secondary (Sternberg) task
Difficulty manipulation (P3 measured in both secondary and primary task)		
Primary task: step tracking (first order predictable, first order unpredictable, second order unpredictable)	Wickens et al., 1983	Increase amplitude of P3 to step changes in primary task and decrease P3 amplitude in secondary task (covert counting auditory targets) with increasing difficulty of primary task
Primary task: one- versus two-dimensional tracking of stepwise moving cursor	Sirevaag et al., 1989	Same result as above
Primary task: system order (velocity versus acceleration condition)		Same result as above
Priority manipulation (P3 measured in both secondary and primary tasks).		
100/0, 90/10, 50/50, 10/90, and 0/100 percentage attention between tasks		
Task 1: dot detection, task-2: visual memory search (CM condition)	Hoffman et al., 1985	Linear trade-off for P3, Large P3s to CM stimuli
Task 1: recognition running-memory (digits), task 2: Sternberg task (CM and VM conditions, set size 1 and 4)	Strayer & Kramer, 1990	Linear trade-off for P3 amplitude (but only in VM condition of task 2). Large P3s to CM stimuli

or visual probes that were embedded in the primary task. Difficulty of the primary task, in which subjects controlled the position of the cursor with a control stick, was manipulated by varying both the number of dimensions to be controlled and the system order. The easy condition was a pure first-order system and the difficult condition was a linear combination of first- and second-order dynamics. Only system order affected the amplitude of P3 for both auditory and visual target stimuli. In the third study (Kramer, Sirevaag, & Braune, 1987) difficulty of the primary task, which consisted of a simulated flight scenario, was manipulated by varying various conditions of the flight task. In the secondary task, subjects pressed a button to deviant tones in an oddball task.

These contrasting sets of results, that is, the fact that primary task difficulty failed to influence secondary task P3 amplitude in the first three studies, but clearly did affect P3 amplitude in the latter three studies, was taken by the authors as strong support for the diagnosticity of P3, that is, that its amplitude is mainly sensitive to processing demands when these demands are perceptual-central in nature. The difficulty manipulation in the first three studies was interpreted as demanding response-related resources, whereas in the last three studies it was assumed to demand primarily perceptual-central resources (see also Donchin, 1981; Donchin, Kramer, et al., 1986; Kramer & Spinks, 1991).

Resource Reciprocity

In the performance domain, dual-task studies have frequently demonstrated the phenomenon of trade-offs: Performance in a secondary task deteriorates as the difficulty of the primary task increases. Inspired by these findings, ERP researchers have argued that if P3 in the secondary task reflects the amount of resources that is available for the secondary task, then P3s elicited by the primary task stimuli should show a concurrent increase in amplitude with an increase in difficulty of this task (see Figure 3). This reciprocal relationship between amplitudes of P3s elicited by stimuli in both primary and secondary tasks was first demonstrated in a study by Wickens et al. (1983). This study used a discrete version of the tracking task that enabled measuring P3 amplitude to targets embedded in the primary task. Task difficulty was varied in two different ways, by varying (a) predictability of stepwise displacements of the target, and (b) first- versus second-order control, that is, the directness of the relationship between the movement of joystick and the movement of the cursor. For both primary task manipulations, an increase of difficulty resulted in an enhancement of P3 elicited by the primary task, and a concomitant reduction of P3 in the auditory secondary task (counting the number of deviant stimuli in an oddball task). An interesting additional finding of this study was that when subjects counted visual probe stimuli that were embedded in the primary task (i.e., counting the stepwise displacements of the target in the primary task instead of deviant auditory stimuli), P3s to the stimuli in the secondary task also increased with higher demands of the primary task.[5]

A reciprocity effect for P3 amplitude was also reported in a later study by Sirevaag et al. (1989). In this study, primary task difficulty was varied in two ways, namely by varying (a) the number of dimensions to be tracked (the target moved in discrete jumps to random positions in one or two dimensions), or (b) the system order, that is, the movement of the joystick increased or decreased the velocity of the cursor or accelerated the movement of the cursor. In the acceleration condition, it was much more difficult to achieve control over the movement of the cursor than in the velocity condition. Again, secondary task P3 declined, and primary task P3 increased in amplitude as a function of system order.[6] In contrast with earlier findings, secondary task P3 also varied significantly as a function of the dimensionality of tracking: Recall that in the study by Wickens et al. (1977), dimensionality of tracking in the primary task failed to affect P3 amplitude in the secondary task. According to Sirevaag et al., these divergent results could be due to the fact that Wickens et al. used a smooth compensatory tracking task, whereas they used a pursuit step-tracking task with abrupt movements. In contrast with compensatory tracking, step tracking was considered as a mental operation that depended more strongly on perceptual-central than response-related resources.

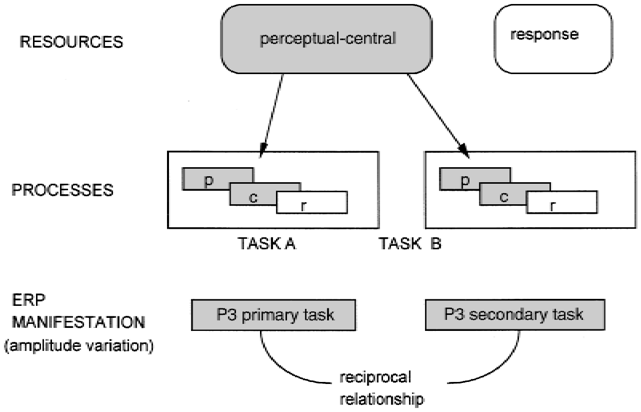

Figure 3. Schematic representation of the way perceptual-central resources (represented as a separate pool of resources that are differentiated from response-related resources) affect processing stages and P3 amplitude in dual-task settings, according to investigators who varied the difficulty of the primary task (p = perceptual, c = central, and r = response processes). Dark areas represent the resources and associated processes presumed to be specifically involved in P3 generation. Amplitudes of P3 elicited in primary and secondary were shown to have a reciprocal relationship

An important aspect of both studies that demonstrated P3 reciprocity was that in the primary task, P3 was always elicited by abrupt changes in the spatial position of the target stimulus. Moreover, these changes were less predictable in the difficult condition than in the easy condition (Sirevaag et al., 1989; Wickens et al., 1983). This means that the increase in P3 amplitude could have reflected stimulus-based attention shifts caused either by the low probability or abruptness of target movements. The same factors could have played a role when system order, another task variable that caused enhancement of P3 in the primary task, was manipulated. In the more difficult second-order control condition, a constant movement of the control stick accelerated the cursor's movement, which might have created a visual impression of abruptness or surprise.

Priority Manipulation

Early P3 studies showed that P3 in an oddball task was strongly suppressed when the subjects directed their attention to another task, like reading a book (see the section "Determinants of P3 Amplitude: Some Early Observations and Hypotheses"). The central question of the two studies reported below was if P3 amplitude would also reflect more graded changes in attention as a function of task priority when subjects have to carry out two qualitatively different tasks simultaneously. In addition, both studies were concerned with the question of to what extent P3 to stimuli that are automatically detected is still modulated by priority instructions. In both studies, P3 amplitude was measured on a single trial basis.

Hoffman, Houck, MacMillian, Simons, and Oatman (1985) measured P3 to stimuli in a CM memory search task and a dot-detection task. In the search task, subjects received training until latency of detection of target letters was independent of the size of the memory set. In accordance with results of single-task visual search experiments reported earlier, CM stimuli in the search task elicited substantial P3s. Furthermore, POC curves showed a linear trade-off between the two tasks for both accuracy of performance and P3 amplitude, suggesting that automatic detection processes still demanded attentional resources. Furthermore, the fact that

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[5] Two further observations are relevant here. First, in the Wickens et al. (1983) study, the reciprocal relationship between P3 to probe stimuli in the primary task and the (auditory) stimuli in the secondary task was not recorded in the same block of trials, but in separate conditions. Second, counting of the stepwise displacement of the target stimuli (i.e., the manipulation that was used to measure the resources demanded by the primary tracking task) was also assigned to the subjects in an additional condition in which they did not perform the concurrent tracking task. In the latter condition, counted targets produced large P3s. Unfortunately, these P3s were not measured separately for the different step displacement conditions (i.e., the low and high predictability conditions). The latter analysis would have offered the unique possibility of assessing effects of automatic attention capture of the stepwise displacements on P3, and its role as a possible confound with processing demands of the tracking task.

[6] In Sirevaag's study, identification of P3 in the primary task was problematical. Inspection of their grand average ERPs gives the strong impression that parietal P3 decreased with increasing load of the primary task. However, when ERP waveforms were submitted to principal components analysis and factor scores were submitted to statistical analysis, primary task P3 increased both a function of increasing the number of dimensions as well as increasing the control order.

priority manipulations affected performance measures but not P3 latency was ascribed to the fact that both tasks also demanded resources at the response level, which were not represented in P3 amplitude but contributed to production of speeded responses.

According to models of development of automatic processing, the pattern of results obtained by Hoffman et al. (1985) would be consistent with "phase 3" processing (Schneider, 1985). According to Schneider, automaticity is a gradual process that consists of several subsequent phases. In early Phases 1 and 2, controlled processes predominate. In Phase 3, automatic processes are dominant, but still require assistance from controlled processes, and in Phase 4, processing has become entirely automatic.

A study by Strayer and Kramer (1990) investigated to what extent trade-offs in P3 amplitude as a function of priority manipulations would differ in automatic and controlled search conditions. They varied the priority of a visual search (Sternberg) task that was carried out together with a recognition running-memory task, which served as a controlled processing baseline condition. The search task had a difficult (memory load 4) and an easy (memory load 2) condition, and was run in two versions: a VM and CM version. In the VM conditions, both priority and memory load manipulations had large effects on P3 amplitude: POC curves showed almost linear trade-offs between the difficult version of the Sternberg task and the running-memory task as a function of task priority, for both detection accuracy (A′) and P3 amplitude. These results were considered as strong support for the view that performance trade-offs can be attributed in part to limited availability of perceptual-central resource.[7]

Furthermore, consistent with earlier single- and dual-task findings, substantial P3s were obtained in the practiced CM tasks, suggesting that CM targets still elicited attention, even when subjects were instructed to ignore these stimuli. Note that in the CM condition, subjects had first received extensive practice until they reached Phase 4 processing, which implies that performance has become completely independent of both memory-load and task-sharing instructions (Schneider, 1985). Although in the Sternberg task, CM targets (like the VM targets) elicited the smallest P3s when this task was completely ignored (priority 0/100% for Sternberg and running-memory task, respectively), these P3s were relatively unaffected by priority and memory load manipulations in the dual-task conditions. These findings were interpreted as consistent with the obligatory, all-or-none character of the automatic attention response as described by Shiffrin and Schneider (1977).

GENERAL CONCLUSIONS AND DISCUSSION

In this section, I shall first recapitulate the major findings of the preceding review, and then formulate some general conclusions with regard to the utility of P3 amplitude as a measure of processing capacity.

Single Task Studies: Multiple Determinants of P3 Amplitude

Three different types of single-task studies were reviewed in the section "Single-Task Studies," namely (a) tasks that used focused or divided attention instructions to two streams of rapidly presented stimuli differing in physical characteristics; (b) choice reaction tasks, which varied the difficulty of processing stages like feature extraction, response choice, and response execution; and (c) tasks that varied complex cognitive operations. The results and conclusions of these studies can be briefly summarized as follows.

(a) When subjects were required to focus attention entirely on one category of stimuli, only target stimuli presented at the attended channel elicited a P3. In these conditions, the high presentation rate in combination with the instruction to focus on physical aspects of the stimuli favored selection on the basis of early selection mechanisms. The P1/N1 complex, which partially overlaps with the early portion of sustained potentials like processing negativity, seems to reflect primarily perceptual/sensory demands of early selection processes. In contrast, the target P3s seems to reflect utilization of resources at a later and more central level of information processing. These P3-related resources are needed to identify the semantic category of stimuli, and are relatively independent of the output of the early processes. Thus, in a multidimensional framework, these findings suggest that ERP components like P1/N1 and P3 reflect demands on separate pools of "perceptual" versus "perceptual-central" resources, respectively (see also Kok, 1997, Kramer & Spinks, 1991, and Parasuraman, 1990, for reviews with similar conclusions).

(b) When task manipulations were used that affect elementary processing stages, stimuli in the more difficult conditions (which usually also showed prolonged reaction times) often elicited smaller P3s than stimuli in the easier conditions. These effects were seen most clearly in experiments that manipulated the perceptual quality of stimuli. These results cannot be ascribed solely to the increased latency variability of single-trial P3s, because they were also found when authors used a latency adjustment procedure. From the set of variables that determine P3 amplitude, information loss or "equivocation" seems to be the most likely source of P3 attenuation in the more difficult perceptual conditions.

It is unfortunate that the same studies provide only little information concerning effects of demands of processes like response selection and response production on P3 amplitude, because these data could have contributed substantially to further validate the hypothesis that P3 amplitude is unaffected by response-related resources, as has been claimed by so many investigators.

(c) The global pattern of results from visual and memory search studies indicated that P3 amplitude was inversely related to the difficulty of controlled search operations. Different factors such as resource reallocation, equivocation, and mutual overlap between ERP components could have influenced P3 amplitude in these tasks. Therefore these results prohibit a straightforward interpretation of load effects in terms of processing resources.

The general implication of studies that used more complex conceptual operations was that stimuli elicited a variety of functionally related slow negative (and sometimes positive) waves. With respect to negative waves, two important observations have been made: (a) their amplitudes depend on the difficulty and duration of complex conceptual operations, and (b) their scalp topography seems to be sensitive to the specific type of cognitive operation that is manipulated in the task. These findings also have important implications for the interpretation of P3 findings in visual and memory search studies, because they demonstrate that task conditions that place a substantial load on working memory processes elicit a qualitatively different category of ERP components that are highly sensitive to the difficulty of these task operations. When these processes and related ERP phenomena occur in

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[7] A separate analysis further verified if these trade-off functions indeed reflected that attentional resources were divided between tasks in a graded manner. Cumulative distributions functions (CDF) on single-trial P3s produced parallel curves for all priority conditions. This means that the distributions of single-trial P3s shifted according to the priority instructions. If subjects, however, had switched attention in an all-or-none fashion between the two tasks across trials, then the CDFs would have shown a mixture of large and small P3s, which was not the case.

the same time frame as P3, they will likely cause reduction of P3 amplitude due to temporal overlap.

Dual-Task Studies

Difficulty Manipulation

A number of dual-task studies that varied the difficulty of the primary task have reported linear trade-offs between amplitudes of P3s elicited in the primary and secondary (oddball) task (earlier section "Dual-Task Studies"). It is not clear to what extent in these studies P3 amplitude variation in the primary task reflected resources that were allocated to this task on the basis of controlled effortful processing, or involuntary processes like orienting and attention capture. Stimuli with properties that elicit orienting or automatic attention shifts are also processed more extensively (as reflected in longer reaction times) than stimuli that do not have these properties. Their effects on performance may therefore be difficult to disentangle from performance decrements caused by other more "endogenous" variables that affect task difficulty, such as task complexity or time pressure (see also Jonides & Yantis, 1988; Theeuwes, 1994; Yantis, 1996).

Note further that in these studies, the nature of the processing demands could only be inferred post hoc from the pattern of P3 results. However, is very difficult to ascertain how the tracking tasks that were used to mimic real-life operational environments permitted a clear separation between perceptual, central, and response processes. For instance, Wickens et al. (1977) assumed that variation of the dimensionality of the direction of tracking primarily tapped resources on the response level. It seems equally plausible, however, that these manipulations also involved perceptual-central processes. Thus, it may be argued that the empirical basis of these dual-task studies is too weak to justify strong conclusions concerning the specific sensitivity of P3 amplitude as a measure of perceptual-cognitive resources (e.g., Kramer et al., 1987; Sirevaag et al., 1989; Wickens et al., 1983).

Priority Manipulation

A few studies have also described dual-task trade-offs as a function of priority manipulations in conditions of both controlled visual search and automatic detection. The general pattern of results of these studies suggests that P3 amplitude reflects demands on a finite supply of attentional resources that are divided in a graded fashion between the tasks. However, in interpreting these results, we are confronted with the same problem encountered in single-task memory search studies. The complex structure of the memory search tasks that served as primary tasks prohibits a clear insight into the specific locus of the effect of these attentional manipulations on P3 amplitude, in terms of processes like encoding, memory search, and target identification. Thus, the only conclusion that seems justified with regard to these studies is that P3 amplitude variation reflected the aggregate demands of both memory search and the target identification processes.

An important additional finding of the same studies was that large P3s were elicited in conditions that favored automatic detection of targets. This provides further support for the view that P3 amplitude and its related resources can also be driven by external events that capture attention, even when the subject is instructed to ignore these events. Note, however, that in contrast to focused attention studies that used high presentation rates, the latter effects were obtained in experiments that used relatively slow presentation rates of stimuli, which could have favored "parallel" processing of the targets in primary and secondary tasks (Lavie, 1995; Lavie & Tsal, 1994).

Utility of P3 Amplitude as an Index of Processing Capacity

Capacity researchers working in the performance domain have generally assumed that allocation of resources can be controlled in two different ways, namely by manipulating priority or by varying difficulty of two tasks that are carried out concurrently (Wickens, 1984). On the basis of the present review, it is concluded that the sensitivity of P3 amplitude as a measure of processing capacity has only been convincingly demonstrated in a restricted number of studies in which capacity allocation was under voluntary control, and the structural characteristics of the task (e.g., task complexity, perceptual quality of stimuli) did not change. Suitable examples are tasks that have manipulated attentional demands by varying the priority of attention allocated to the primary and secondary tasks (Duncan-Johnson & Johnson, 1977, 1982; Mangun & Hillyard, 1990; Strayer & Kramer, 1990) or by instructing subjects to focus attention to specific stimulus features (e.g., Hansen & Hillyard, 1983; Näätänen, 1992).

Interpretation of effects of task difficulty on P3 amplitude within a resource framework are more problematical. Intuitively, an increase in task difficulty leads to investment of more effort and should thus also produce larger P3s. However, task manipulations that increase task difficulty are often also responsible for changing the task structure (Kantowitz, 1987; Navon & Gopher, 1980). These structural factors could interfere with the very processes that underlie P3 generation, namely the identification of stimulus features that determine if the stimulus is a target or belongs to a certain semantic category. In these cases, the stimuli in the more difficult conditions will elicit smaller P3s. In other cases, structural factors could have been responsible for producing the opposite effect, namely an enhancement of P3 amplitude in the more difficult task conditions (i.e., conditions that produced more errors in performance). A suitable example is the enhancement of P3s elicited by abrupt changes of stimuli embedded in the primary tasks in dual-task conditions (the reciprocity effect reviewed in subsection "Difficulty Manipulations"). Here, P3 enhancement could very well have resulted from certain salient properties of the eliciting stimulus and not by increased internal demands of the primary task.

With respect to the specificity, or diagnosticity, of P3, it is concluded that the complex structure of the tasks that were used in many studies prohibits a straightforward interpretation of P3 results in terms of underlying processes and related resources. Another problematic factor relates to the complex nature of P3 itself. P3 is probably not a unitary phenomenon, but represents a complex waveform that comprises several functionally distinct and mutually overlapping subcomponents. In the present review, we have seen that, in particular, overlap between P3 and sustained negative waves could lead to considerable distortion of P3 in task conditions in which these waves are active in the same time frame as P3. Overlap between P3 and slow negative potentials also prohibits a sharp functional separation between subprocesses in the perceptual-central domain, on the basis of ERP components. Other potential sources of overlap could be phasic components that are active in the same period in which P3 is active. For instance, some studies have suggested that the P3 complex may contain several subcomponents that reflect not only processes in the perceptual and central domain, but also response-related processes like response selection (e.g., Falkenstein et al., 1994, 1995).

P3 and Event Categorization: Interaction of Neural Systems for Attention and Memory

Figure 4 presents a model of P3 amplitude that further specifies its role with respect to capacity allocation. It must be emphasized that it is not the intention to present a new model to be added to the already crowded set of theories of P3. The present model is highly eclectic and should be seen as an attempt to integrate the major (and sometimes paradoxical) experimental findings that were reviewed in the present paper. Note also that the model mainly applies to the "target P3" or "P3b" component that was the focus of the present review. It further specifies some important distinctions made in the present article with respect to (a) factors that determine capacity allocation and (b) neurocognitive mechanisms like attention and working memory that are responsible for the control of event categorization processes. I shall briefly recapitulate the central elements of the model.

Event Categorization

The core element in the model is the assumption that P3 amplitude reflects attentional capacity invested in categorization of task relevant (or significant) events. Event categorization (in the above sense) is conceived of as a process that leads to the decision that the external stimulus matches (or does not match) with an internal representation of a specific event or category of stimuli. A suitable example of such a category are target stimuli. Note that although targets (matches) elicit larger P3s than nontargets (mismatches) at equal levels of probability (Duncan-Johnson & Donchin, 1977; Looren de Jong et al., 1988; Lorist et al., 1994; van der Stelt et al., 1998), nontarget stimuli will often also elicit substantial P3s.

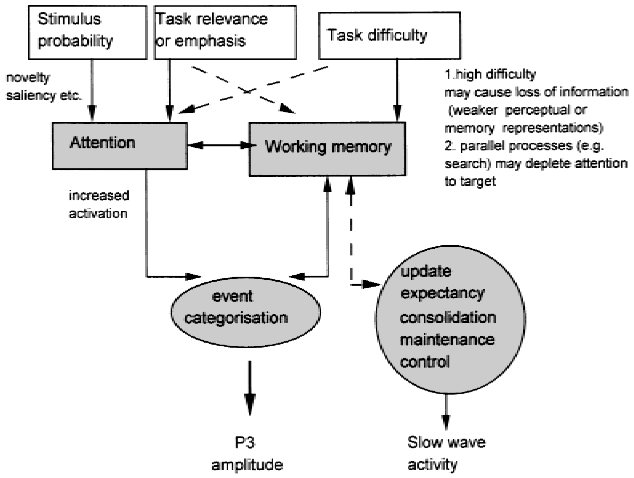

Figure 4. A simplified diagram describing the major determinants of P3 amplitude (white boxes), the underlying mechanisms (dark boxes), and their effects on the event categorization process. Event categorization is conceived of as a process that involves a comparison between the external stimulus and an internal representation, and that is elicited by target as well as nontarget (or even novel) stimuli. Low probability (or high saliency and novelty) of events and task relevance (left) are assumed to increase activation of neural assemblies associated with event categorization, thus leading to larger P3s. Conversely, task difficulty (right) is assumed to counteract this process, leading to smaller P3s. It is further assumed that slow wave activity is associated with a variety of working memory processes (e.g. encoding, update, search) that are under executive control and that run in parallel or precede event categorization. See text for further explication.

Event categorization involves both perceptual and central processes, as the meaning of a stimulus or category of stimuli (e.g., "it's a target" or "it's not a target") can only be established after some contact between the perceptual system and the memory system has taken place. Prior studies have also referred to this processing stage as a response set (Broadbent, 1971) or a stimulus identification (Sanders, 1990; van der Molen, Bashore, Halliday, & Callaway, 1991) mechanism. In contrast to the stimulus set or early filter mechanism that is tuned to physical characteristics of stimuli, a response set may be described in terms of a filter that is tuned to memory-dependent characteristics of stimuli, such as the semantic features of a chosen target stimulus.

There are many studies suggesting that the scalp-recorded P3 in humans is generated in networks that comprise temporal-parietal neocortical areas as well as higher limbic structures such as the anterior cingulate. This evidence comes from various sources, such as lesion and intracranial studies (Hallgren et al., 1980; Hallgren et al., 1995; Hallgren, Marinkovic, & Chauvel, 1998; Johnson 1989a,b; Knight, 1998; Knight & Grabowecky, 1995; Verleger, Heide, Butt, & Kompf, 1994), functional neuroimaging studies (McCarthy, Luby, Gore, & Goldman-Rakic, 1997; Menon, Ford, Lim, Glover, & Pfefferbaum, 1997; Opitz, Mecklinger, von Cramon, & Kruggel, 1999; Stevens, Skudlarski, Gatenby, & Gore, 2000), and studies using the scalp recorded magneto-encephalogram (Rogers et al., 1991; Mecklinger et al., 1998). However, the question of how event categorization (or the decision that the event is a target or a nontarget) is implemented in these cortical networks still remains to be answered (see also Linden et al., 1999). Desimone, Miller, and Chelazzi (1994) made an interesting attempt to describe the computational properties of such a mechanism in order to account for findings of visual recognition studies in monkeys. They proposed that cell assemblies in inferior-temporal (IT) cortex function like an adaptive filter that causes progressive focusing or narrowing of activity in IT cells after a stimulus has become familiar. Top down mechanisms are able to bias the filter (e.g., through pathways from prefrontal cortex), resulting in enhanced focusing of target features. Such a mechanism could underlie both the novelty P3 (which habituates after repeated stimulus presentation) but also the target P3 that is generated after events have become completely familiar. Following the same reasoning, Kok (1997) suggested that a target identification mechanism as reflected in P3 can be conceptualized as a set of neural elements or "recognition units" that form a neural network. The primary function of the network is to compare stimulus attributes with an internal representation of the target.

Attention

The strength of activation of event categorization (or recognition) networks depends not only on the closeness of the match between features of the stimulus and the representation of the target, but also on the amount of attention that is paid to the stimulus. In experimental settings, this is usually achieved by means of manipulation of relative emphasis of a stimulus or task. For instance, when a subject is selectively tuned to certain target features in a focused-attention task or searches for a particular familiar object such as a target in a visual display, attentional mechanisms may bias cells in cortical association areas that code target characteristics (LaBerge, 1995). This may result in enhanced activation of neural assemblies when a target is presented, that is, when a complete match with the critical stimulus occurs. According to this view, nontargets can also produce substantial P3s, as long as these stimuli receive attention and have not been filtered out on the basis of their sensory characteristics (like irrelevant stimuli in high-speed focused-attention tasks).

Figure 4 further indicates that low probability stimuli may also gain access to attentional and event categorization mechanisms. Suitable examples are meaningful or low probability events that are presented at unattended "channels" in focused attention tasks. These "irrelevant" stimuli may still elicit substantial P3s because they (a) capture attention automatically and (b) partially match with the internal representation of the target. Similar attention and P3 effects may be elicited by novel, highly distinctive or salient stimuli. For instance, novel events often elicit both a frontal component ("novelty P3") and a posterior component. The posterior component has the same topographical distribution as the P3(b) (Spencer et al., 1999) and could reflect activation of the same neural assemblies that are activated by task-relevant events such as targets. Another example is P3s elicited by CM targets in low priority memory search tasks (see subsection "Priority Manipulation"). These P3s are more likely to occur when processing load is low and there remains sufficient spare capacity to be captured by the eliciting event. Thus, both active focusing of attention and passive orienting may increase activation of cell populations associated with categorization of events.

Working Memory

Working memory is another important mechanism that is involved in the generation of P3. It is considered as a state of the processing system that is controlled by attention. Attention also depends on working memory. This is because the maintenance of active attentional preparation of a perceptual event or some form of action requires that the representation of the target is stored for some time in working memory.

The present review contained many examples of tasks in which identification of the target depended on sustained processes such as expectations, memory search, mental rotation, or more complex conceptual and semantic operations. An assumption of the model presented in Figure 4 is that, although the generation of P3 depends on these processes, P3 amplitude itself reflects a more discrete (all-or-none) process, namely categorization of events (e.g., target/nontarget, infrequent/frequent) that may be seen as the outcome of these sustained processes. It is further proposed that the higher order or "executive" mechanisms that control typical working memory operations (expectations, memory search, etc.) activate a neural system different from that involved in simple sensory discrimination or event categorization. This neural system probably recruits a widely distributed network with reciprocal connections between prefrontal and posterior association areas (e.g., Goldman-Rakic, 1988; Cavada & Goldman-Rakic, 1989; LaBerge, 1995). The maintained activity of this system may help to solidify memory traces or serve as a visual "sketchpad" or verbal "rehearsal loop" for comparing external stimuli with internal representations (Baddeley, 1986, 1992; Posner & Peterson, 1989; Posner & Raichle, 1994). This activity is assumed to be primarily reflected in negative slow wave activity (see also Rösler et al., 1993, 1997).

Figure 4 further suggests that these more sustained executive processes may either precede or operate in parallel with the event categorization process. Thus, a potential problem in testing this model is that, although complex internal processes like memory search may be functionally separated from their end product, that is, categorization of a relevant event, these processes and consequently also their ERP manifestations may often overlap in time. Future studies should therefore also pay attention to other techniques developed in cognitive neuroscience that allow a combination of anatomical data derived from neuroimaging techniques and time-course data derived for ERPs. This approach will perhaps allow a more precise identification of the brain systems and networks underlying complex recognition processes and their contribution to generation of P3.

Task Difficulty

A task can be made more difficult by limiting the quality of perceptual data or by increasing the informational load on internal (working memory) operations. A greater load on working memory is usually achieved by increasing the complexity of task operations (e.g., number of items held in memory or presented on the display or the complexity of arithmetical operations; see also footnote 3). Task difficulty (or its subjective derivate, equivocation) is another important determinant of P3 amplitude. However, this variable is assumed to counteract the facilitatory effect of task relevance (or emphasis) on the event-categorization process. As argued earlier, this is because task difficulty is assumed to transform the structure or actual content of the flow of information in the processing systems, thereby interfering with the event-categorization process, whereas attention is assumed to modulate (e.g., enhance or attenuate) the information flow.

How does greater task difficulty interfere with categorization of task relevant events? One possibility is that target stimuli that are perceptually degraded or that are presented in high-load conditions will produce weaker matches with recognition units, and hence smaller P3s. For instance, in visual search tasks, an increase in memory or display load will also produce an increase in the number of mismatches, that is, the number of stimuli belonging either to the memory set or display set that do not match with the critical stimulus. Another possibility is that difficult tasks often contain task elements that deplete attention or resources allocated to perceptual events (see Figure 2 for a specific example).

The model of Figure 4 finally also incorporates the possibility that an increase in task difficulty can restrict the capacity available for additional task operations or stimuli (see the dotted line between Task difficulty and Attention). This option is included to accommodate findings from dual-task experiments that reported a graded effect of primary task difficulty on the amplitude of P3 in the secondary oddball task (Isreal, Chesney, et al., 1980; Isreal, Wickens, et al., 1980; see also subsection "Difficulty Manipulations"). An important feature of these experiments is that the structure of the secondary task in which the eliciting stimuli were embedded did not change with increasing difficulty of the primary task. Thus, the smaller P3 amplitude in these tasks could have resulted from a true reduction of attentional resources and not from structural factors like information loss (or equivocation) in the recognition units.

Other Proposals

The present conceptualization of P3 has much in common with proposals that have linked P3 with "template matching" (Chao, Nielsen-Bohlman, & Knight, 1995; Ford, 1978; Squires, Hillyard, & Lindsay, 1973). When subjects are preset to detect a certain target stimulus, they develop a neural representation or template of the stimulus. The closer the match between incoming information and the template, the larger the amplitude of P3. This hypothesis receives support from a number of studies that have demonstrated that P3 (or P3-like waves) are sensitive for the relative familiarity of words (Rugg & Doyle, 1992; Smith & Hallgren, 1989) or geometrical patterns (Kok & Looren de Jong, 1980b). Additional support comes from signal detection experiments showing that P3 amplitude increases as a function of the hit rate and rated confidence in detected stimuli (Kerkhof & Uhlenbroek, 1981; Parasuraman & Beatty, 1980; Squires et al., 1973; Sutton, Ruchkin, Munson, Kietzman, & Hammer, 1982). These results strengthen our earlier assumption that P3 reflects processes that underlie recognition memory (i.e., the awareness that a stimulus belongs or does not belong to the category of a certain memorized target event).

According to event-categorization and template-matching models, P3 also embodies working memory processes that are associated with the conscious perception of target events. This is because both event-categorization and match/mismatch processes always imply a comparison between an external sensory event and internal representation or template of the event categories. Note, however, that in these models, P3 is considered to be a reflection of the end product of working memory operations (i.e., the final event categorization or match/mismatch decision) rather than these operations themselves (e.g., search or maintenance of memory traces). The involvement of working memory in the generation of P3 was also suggested in another influential model of P3 namely the "context-updating" hypothesis (Donchin, 1981; Donchin & Coles, 1988; Donchin & Fabiani, 1991; Donchin, Fabiani, Packer, & Siddle, 1991; Fabiani, Karis, & Donchin, 1986). According to this theory, target stimuli are compared with the content of working memory and updated or reorganized as a function of the incoming information. Updating of representations in working memory is further assumed to be an important mechanism underlying consolidation of new information and the facilitation of subsequent recall (Fabiani, Karis, & Donchin, 1990). However, to date no strong empirical evidence has been presented to support the view that modulation of P3 amplitude by stimulus events indexes strength of encoding or consolidation, or has some causal relationship to subsequent memory performance (see Rugg, 1995, and Verleger, 1997, for reviews dealing with this and related P3 models; and Sanders & Collet, 1988).

Thus, according to the model presented in Figure 4, updating of memory traces is not essential for the generation of P3. A context updating mechanism as described by Donchin (Donchin, 1981; Donchin & Coles, 1988; Fabiani et al., 1986) could, however, play a role during involuntary orienting to novel stimuli, in which a revision of a neuronal model is required after a mismatch has occurred between incoming information and an internal representation (Öhman, 1979; Sokolov, 1963). These conditions typically elicit a more frontally distributed P3 response (P3a, novelty P3) that shifts to a more posterior distribution with event repetition (Courchesne, 1978; Friedman & Simpson, 1994). This could reflect that subjects gradually revise their internal representations while they learn to categorize initially novel events.

Another proposal is that P3 is generated during "closure" of a perceptual cycle (Verleger, 1988). Closure theory comes in two intrinsically related versions, a neurophysiological version and a cognitively oriented version. The neurophysiological version was originally formulated by Desmedt (1980) who defined closure as "a transient reduction of cerebral neuromodulation pressure that is achieved though inhibition of the mesencephalic reticular formation by prefrontal cortex" (p. 684). At present, no data are available that confirm this theory. For instance, there is no direct evidence that P3 is systematically related to electrocortical potentials that occur prior to P3 like the CNV (e.g., Donchin, Tueting, Ritter, Kutas, & Heffley, 1975). There are also no indications that the amplitude or latency of P3 to target stimuli is correlated with preceding negative potentials that reflect selective attention to specific stimulus features (Hansen & Hillyard, 1983; see also Näätänen, 1990, p. 218).

In its cognitive version, closure has been described in terms of poststimulus cognitive activities that lead to the decision that a signal belongs to a task-relevant category (Desmedt, 1980 p. 684; Verleger, 1988). The latter definition seems to have much in common with our description of event categorization processes and how they relate to P3. Similar to the event categorization model presented in Figure 4, Verleger's model predicts that P3 amplitude is (a) positively related to the closeness of the match and amount of attention invested in processing of stimuli, and (b) negatively related to task difficulty.

An advantage of the event categorization model as presented in this article is that it is free from the neurophysiological constraints imposed by closure and gives us more specific clues to what the system underlying generation of P3 is "doing." An additional feature of the model that is lacking in other theoretical proposals is that it specifies in more operational terms the specific interactions that could occur between attention and memory functions, and how they are expressed in ERP components like P3 and slow wave.

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