An EEG/ERP study of efficient versus inefficient visual search

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Abstract

Visual search involves perception, attention, memory, and response selection. In this EEG/ERP study, we investigate how these components change with the type of search. Participants identified the location of a target item (coloured, oriented rectangular bar) in search displays also containing non-target distractors. In the condition yielding efficient search, where response time was independent of set size (two or four items), distractors had no feature in common with the target. In the condition yielding inefficient search, where response time increased with set size, distractors shared one feature (either colour, or orientation) with the target. Stimulus- and response-locked event-related potentials (P1, N1, P2, N2, P3, and rLRP) were analyzed. P3, an indicator of working memory engagement, showed no significant difference in onset latency between efficient and inefficient conditions. Although P3 peak amplitude was smaller, activity over time was greater for inefficient search. The duration of response-locked lateralized readiness potential (rLRP), indicating response selection, was also longer in the inefficient condition. By contrast, indicators of selective attention, P1 peak amplitude and N1 peak latency, were sensitive to number of items; and P2 peak amplitude to number of non-target features. (N2 results were inconclusive.) These results suggest a difference between efficient and inefficient search that lies not in the time required to select items as potential targets of search (selective attention), but in the time required to confirm which of those items is indeed the target (target confirmation).

Keywords: Visual search; attention; similarity; EEG; ERP; P3; rLRP; synchrony; phase-locking

Introduction

Visual search is generally conceptualized as involving an interaction between bottom-up perceptual information processing versus top-down processing of contextual information by working memory (see Corbetta & Shulman, 2002; Desimone & Duncan, 1995, for reviews). Reflecting this distinction, some models of visual search include two types of computation based on (1) the relationships between items in the search display independent of the target item; and (2) the relationships between display items and the currently searched for target (see, e.g., Duncan & Humphreys, 1989; Wolfe, Cave, & Franzel, 1989). Such models have accounted for the well-established effects of target-distractor and distractor-distractor similarity on search efficiency. Respectively, they are the increase and decrease in search time per display item (i.e., search slope, or conversely efficiency) with more items sharing the same features (e.g., colour, or orientation). When the target is uniquely identifiable by a single feature, search time is typically independent of the number of display items (efficient search), else it increases linearly with item number (inefficient search). The way in which bottom-up (possibly parallel) and top-down (possibly serial) processes interact to determine search efficiency, though, remains unclear despite decades of intensive research (see Wolfe, 2003, for a review).

EEG/ERP affords a non-invasive alternative for discerning visual search subprocesses (e.g., Luck & Hillyard, 1990; Wolber & Wascher, 2003). Although there are well-developed theories of visual search at the behavioural level, relatively little neuroimaging work has provided the necessary *bridging laws* that afford rigourous testing via correspondences to the neurophysiological level (Coltheart, 2006). Hence, our approach is primarily exploratory. That is, to map out and contrast the temporal relationships between putative EEG/ERP markers of cognitive processes under efficient and inefficient search conditions, which motivates a more hypothesis-driven approach for future studies.

Methods

Participants

Eleven Japanese university students (aged 24 ± 3.4 years; male; one left handed) with normal, or corrected-to-normal vision, were paid to participate in the experiment.

Apparatus and stimuli

A standard desktop computer was used to present stimuli. Stimuli were rectangular bars, either red, green, blue, or yellow; and at an orientation of 0°, 45°, 90°, or 135° degrees from horizontal. The background color for all trials was grey. The display was divided into four equal quadrants by invisible horizontal and vertical centerlines. A quadrant contained at most one stimulus item, jittered about its center so that the location of the target was clearly identifiable by the containing quadrant. Electrical potentials were collected using a digital electroencephalograph system (Nihon Kohden Neurofax EEG-1100) with an Ag/AgCl electrode cap.

Conditions and procedure

There were two search display type conditions: *efficient*, where distractors shared no feature with the target so that response times are independent of search set size; and *inefficient*, where distractors shared one feature (either colour, or orientation) with the target so that response times increase with size. Set size was two or four items. The display type-size conditions are labeled, Eff-2, Eff-4, Ineff-2, and Ineff-4 for efficient and inefficient, two and four item conditions, respectively. Eff-4 corresponds to a *popout* condition, and Ineff-4 corresponds to a *conjunctive* search condition.

Each trial commenced with a fixation period (1500 ms) where participants focused on a small white ring placed at the center of the screen. The fixation was then replaced by a target cue (1000 ms), positioned at the screen center. The target was then replaced by a second fixation delay period (1000 ms). Following this delay period, a search set of items was displayed for 2500 ms, or until a key was pressed, whichever came first. Participants were required to identify the target location within this time period by pressing a key corresponding to the quadrant within which the target was located. Speed and accuracy of response were stressed. Participants pressed either key ‘a’ (upper left), or ‘z’ (lower left) with their left hand; or ‘k’ (upper right), or ‘m’ (lower right) with their right hand to identify the respective quadrants. The assignment of stimulus items to quadrants was randomized and responses were counterbalanced across trials. Trial timing and example search displays are shown in Figure 1. Trials were blocked by display type. There were 64 trials per block. A prompt, displayed for 10 s, indicated the start of the next block. There were 3 blocks for each display type, totaling 6 blocks per session. Each participant did two sessions, separated by about 5 min of rest. Thus, each participants received 768 experiment trials (= 2 sessions x 6 blocks x 64 trials). Response keys and times were recorded. Pressing an incorrect key, or failure to respond within the maximum allotted time was regarded as an error.

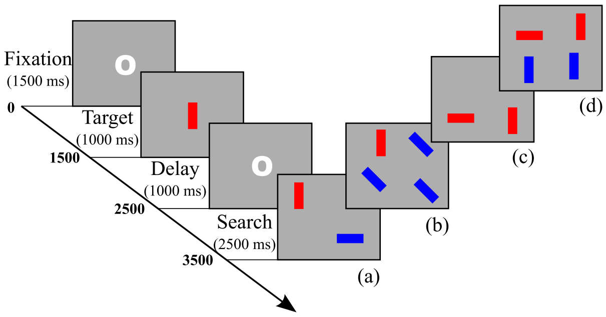

Figure 1: (a) Eff-2, (b) Eff-4, (c) Ineff-2, and (d) Ineff-4.

Electroencephalograms (EEG) were measured from the following 19 electrode sites of the International 10-20 system: Fp1, Fp2, F7, F3, Fz, F4, F8, T3, C3, Cz, C4, T4, T5, P3, Pz, P4, T6, O1, and O2, with AFz as the ground electrode. Electrooculograms (EOGs) were recorded to monitor possible eye movement artifacts. Electrodes were attached with gel to reduce impedance to below 5 kΩ. EEG and EOG were digitized at a rate of 1000 Hz, and were band-pass filtered at 0.032 Hz and 300 Hz. The experiment was conducted inside an electrically shielded room.

Analysis

Behavior Analyses of variance (ANOVAs) were conducted on response errors and times. Response time analysis was done after removing error and outlier trials. Data were entered into two (display type) by two (display size) repeated measures ANOVAs to infer significant effects. For errors, an arcsine transform ($arcsin\sqrt{x}$) was applied to error rates before computing analyses of variance. Newman-Keuls tests were employed for all post hoc analyses unless otherwise stated.

EEG/ERP EEG data were re-referenced offline to the mean of earlobe potentials A1 and A2. Event-related potentials (ERP) were time-locked to the onset of search display for stimulus-locked ERP analysis, or response key for response-locked ERP analysis. For stimulus-locked ERP analysis, a data window was set at -200 ms to 1000 ms relative to stimulus onset. For response-locked ERP analysis, a window was set at -500 ms to 50 ms relative to response onset. Trials containing artifacts (approximately 25% of trials, identified by visual inspection) or response errors were excluded from further analysis. Eye-movement artifacts were removed using Independent Components Analysis.

The amplitudes and latencies of P1, N1, P2, N2, and P3 components were estimated at the most dominant midline sites (Fz for P2 and N2; and Pz for P1, N1, and P3). The P1, P2, and P3 components were defined as the largest positive-going peaks occurring within a 80–180 ms, 100–250 ms, and 200–800 ms latency window, respectively. The N1 and N2 components were defined as the largest negative-going peaks occurring within a 120–240 ms and 150–400 ms latency window, respectively. The peak amplitudes and latencies for each participant in each condition were entered into ANOVAs. Of particular interest to this study is the P3 component as an indicator of the onset and duration of working memory processes. For this component, more specific analyses were conducted in addition to an ANOVA for peak amplitude. The *jackknife* method (Miller, Patterson, & Ulrich, 1998) was used to estimate the P3 onset latency. Here, we used an absolute criterion of 6 μV (approximately half of peak amplitude) instead of a relative criterion, which has been recommended in general (Kiesel, Miller, Jolicoeur, & Brisson, 2008). The P3 component may diminish in amplitude and increase in latency with larger display sets, possibly due to jitter generated by shifting attention to other items to be matched to a target (Kok, 2001). In this case, an absolute criterion is more likely to index the onset of the first attended item to be matched to the target. To estimate the duration of working memory processes, we use the amount of activity integrated over time (i.e., the area under the ERP curve). These estimates are then entered into an ANOVA to determine effects on working memory duration. Following the jackknife procedure (Kiesel et al., 2008), ANOVAs of P3 onset latency used the corrected F-test (Fc). For rLRP, the activity was calculated as the contralateral minus ipsilateral central electrode relative to the overt response. That is, C4 - C3 (C3 - C4) for left (right) responses. Similar to the analysis of P3, the jackknife method with an absolute criterion of -1.75 μV (approximately half of peak amplitude) was used to estimate rLRP onset latency. The onset latencies for each participant in each condition were entered into an

ANOVA using the corrected F-test.

Results and discussion

Behaviour

An ANOVA revealed significant effects of display type, $F(1,10) = 10.61$, $p < .009$, and display size, $F(1,10) = 5.01$, $p < .049$, on errors. The error rate was greater in the inefficient than efficient condition, and greater in set size two than four condition. The interaction of type and size was not significant, $F(1,10) = 1.51$, $p = .248$. For response times, there were significant effects of type, $F(1,10) = 101.28$, $p < .00001$, and size, $F(1,10) = 73.64$, $p = .00001$. There was also a significant type by size interaction, $F(1,10) = 55.90$, $p = .00002$. Post hoc analysis revealed significant differences between Ineff-2 and Ineff-4, p = .0004, Eff-2 and Ineff-2, p = .002, and Eff-4 and Ineff-4, $p = .0002$, but not between Eff-2 and Eff-4, p = .873. Mean untransformed error rates and response times are shown in Table 1.

Table 1: Mean response error rates and times (ms).

	Eff-2	Eff-4	Ineff-2	Ineff-4
Error	.050	.037	.069	.061
RT	429	432	524	632

EEG/ERP

P1 and N1 For the P1 component, a two-way ANOVA for the dominant channel (largest peak amplitude at the midline), Pz, revealed a significant effect of set size on amplitude, $F(1,10) = 20.94$, $p = .001$. There was no effect of set type, $F(1,10) = 1.01$, $p = .339$, and no interaction, $F(1,10) = 0.52$, $p = .488$. For latency, a two-way ANOVA did not reveal significant effects for type, $F(1,10) = 0.14$, $p = .713$, or size, $F(1,10) = 0.70$, $p = .422$. For the N1 component, an ANOVA at Pz did not reveal any significant effects for type, $F(1,10) = 1.80$, $p = .209$, size, $F(1,10) = 0.12$, $p = .913$, or their interaction, $F(1,10) = 0.68$, $p = .430$ on peak amplitude. There was a significant effect of size on latency, $F(1,10) = 8.42$, $p = .016$, but not type, $F(1,10) = 0.01$, $p = .942$. The type by size interaction was not significant, $F(1,10) = 0.68$, $p = .430$. Mean P1 and N1 peak amplitudes and latencies are shown in Table 2(a).

A likely explanation for the effects of P1 and N1 is that they reflect stimulus intensity, or overall display luminance, which is greater in set size four than two conditions. Although P1 and N1 indicate location-modulated stimulus processing (i.e., larger peaks when attending to the location of a stimulus than when attending to an empty location), the effects are supposed to be contralateral to stimulus location (Luck, Woodman, & Vogel, 2002). No such systematic differences were observed here. Another explanation for the N1 component is as an indicator of item discrimination (Vogel & Luck, 2000). It is unlikely that discrimination is the basis of the latency effect observed here. Discriminability should be more difficult in the Ineff-2 and Ineff-4 condition, eliciting larger N1 peaks, since items were more similar to the target than in the Eff-2 or Eff-4 conditions. However, Ineff-4 peak was smaller than in the Eff-4 peak, and the Ineff-2 peak was smaller than the Eff-2 peak.

Table 2: ERP amplitudes (μV) and latencies (ms).

	Measure	Eff-2	Eff-4	Ineff-2	Ineff-4
(a)	P1 amp.	3.77	5.71	3.79	5.28
	P1 lat.	125	126	127	122
	N1 amp.	-4.42	-4.41	-3.99	-4.10
	N1 lat.	191	174	188	176
(b)	P2 amp.	3.40	4.15	2.41	3.41
	P2 lat.	192	180	193	172
	N2 amp.	-1.66	-1.64	-1.90	-1.90
	N2 lat.	236	252	252	267
(c)	P3 amp.	13.16	13.82	12.03	11.27
	P3 area	5.05	5.38	5.50	6.48
	P3 lat.	359	365	373	396
	P3 onset	276	273	282	259
(d)	rLRP lat.	152	161	184	207

P2 and N2 For P2, an ANOVA of peak amplitude for the channel with the largest peak amplitude at midline, Fz, indicated significant main effects of type, $F(1,10) = 10.87$, $p = .008$, and size, $F(1,10) = 5.85$, $p = .036$, but no significant interaction, $F(1,10) = 0.22$, $p = .646$. There were no significant main effects on peak latency for type, $F(1,10) = 0.76$, $p = .404$, or size, $F(1,10) = 1.81$, $p = .208$. For N2, there were no significant main effects on peak amplitude, $F(1,10) = 1.44$, $p = .258$ (type), $F(1,10) = 0.002$, $p = .969$ (size), and $F(1,10) = 0.001$, $p = .973$ (interaction). There were no significant effects on peak latency, $F(1,10) = 1.88$, $p = .201$ (type), $F(1,10) = 1.98$, $p = .190$ (size), and $F(1,10) = 0.005$, $p = .947$ (interaction). Mean peak amplitudes and peak latencies for the P2 and N2 components at Fz are shown in Table 2(b).

The larger P2 peaks for efficient than inefficient conditions and the lack of a peak latency effect suggest that processes specific to inefficient search were not invoked at this point. If the P2 peak for inefficient search was larger, then this result may suggest, for example, greater top-down control of attention during inefficient search. Instead, the evidence suggests that components specific to inefficient search must emerge at a later stage of the overall visual search process. P2 amplitudes also correlated with number of non-target features. Peak order (non-target features) were: Eff-2 (2) $<$ Eff-4 (6) and Ineff-2 (1) $<$ Ineff-4 (3), contrasting set size; and Eff-2 (2) $>$ Ineff-2 (1) and Eff-4 (6) $>$ Ineff-4 (3), contrasting set type, suggesting that P2 reflects top-down processes driving feature suppression as the basis for selective attention.

P3 For the channel with the highest peak amplitude at midline, Pz, there was a significant effect of type, $F(1,10) =$

19.97, $p = .001$, but not size, $F(1,10) = 0.03$, $p = .873$, nor interaction, $F(1,10) = 2.03$, $p = .184$. There were no significant effects on P3 peak latency, $F(1,10) = 2.66$, $p = .134$ (type), $F(1,10) = 1.10$, $p = .320$ (size), and $F(1,10) = 0.49$, $p = .498$ (interaction). There were no significant effects on P3 onset latency, $Fc(1,10) = 0.08$, $p = .778$ (type), $Fc(1,10) = 0.59$, $p = .459$ (size), and $Fc(1,10) = 1.95$, $p = .193$ (interaction). Figure 2 shows the ERPs in the four search conditions for the Pz channel. Evidently, although the latencies were similar, the peaks were more extended over time in the two inefficient search conditions. An analysis of activity integrated over time (area under the curve) for the time period 200-800 ms after stimulus onset showed a significant effect of type, $F(1,10) = 36.55$, $p = .0001$, and a marginally significant effect of size, $F(1,10) = 4.38$, $p = .063$, but no interaction, $F(1,10) = 1.80$, $p = .210$. P3 peak amplitudes, areas, and peak and onset latencies are shown in Table 2(c).

Previous research has identified a variety of task conditions affecting P3 amplitude and latency, including task relevancy, target probability, task difficulty, practice and perceptual and memory load (see Kok, 2001; Polich, 2007, for reviews). Against this background, it is surprising that we observed no significant difference in P3 onset latency for efficient and inefficient visual search. We suppose that P3 reflects a working memory process for matching attended items to the target held in short term memory (Kok, 2001). A model that involves either parallel or serial matching may be consistent with this result. In the parallel case, the matching process is engaged regardless of the items selected for attention, so P3 onset latency is independent of set type, or size. In the serial case, P3 onset latency may reflect matching of the first attended item to the target, so here too onset latency does not change with set type, or size. In regard to P3 peak latency, it is perhaps also surprising that we did not find a significant effect given that Hoffman, Simons, and Houck (1989) observed increased P3 peak latency with set size (one, or four) in the inefficient condition. Although in our case, the trend was in the same direction (i.e., Ineff-4 > Ineff-2), the two results may not be comparable. For Hoffman et al. (1989), peak latencies were greater than overt response times, suggesting that their latency results reflect additional generators of P3 not specific to working memory.

There are two possible explanations for the difference in P3 peak amplitude that derive from serial versus parallel models of search, again assuming P3 reflects matching processes. In the serial case, the smaller peak amplitude may result from trial-by-trial latency variation. We supposed that P2 reflected selective attention via distractor feature suppression. For the efficient conditions, selective attention leaves only one candidate item for subsequent matching to the target, since none of the distractors have a target feature. In the inefficient conditions, selective attention does not eliminate any items, because all items share at least one feature with the target. Consequently, the target may not be located until the second, third, or even fourth attempted match. In this case, the averaged peak potentials will be lower but more distributed over time, which is consistent with the observed type and size effects on integrated activity. In terms of P3 peak amplitude, our results are consistent with Hoffman et al. (1989). Wolber and Wascher (2003) also observed decreased P3 peak amplitude with set size (from 5 to 30 items) for inefficient (conjunctive) search. Luck and Hillyard (1990), by contrast, observed increased P3 peak amplitude with set size for inefficient search. But, as Luck and Hillyard also noted, these disparate results may be due to a difference in the set size range in relation to memory capacity. In our case, and also that of Hoffman et al. (1989), displays contained no more than four items. For Luck and Hillyard (1990), display sizes were at least eight, and so more likely required serial attention. In the parallel case, the smaller amplitude may be due to a form of resource (re)allocation (Kok, 2001; Polich, 2007), where attention is (spatially) distributed among more items resulting in a smaller peak. Yet, because the attended items are more similar to each other the time to determine the target is longer, hence the greater amount of activity over time in the inefficient conditions.

From the combination of P3 peak amplitudes and areas, we surmise that the durations of working memory processes were longer in the inefficient conditions. This difference in duration is implied by observing that the amplitudes were lower and areas greater in the inefficient conditions, therefore the durations must be longer.

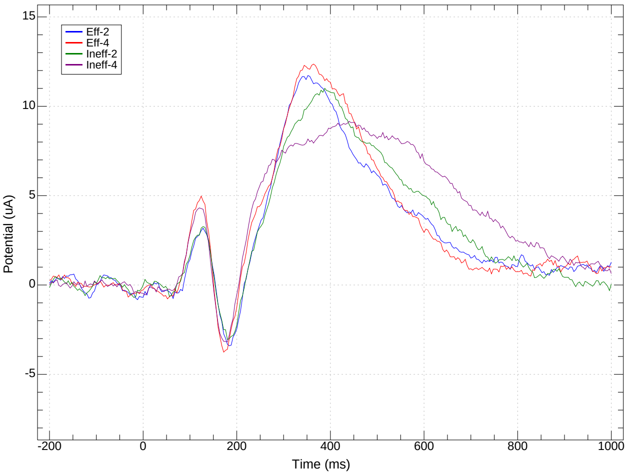

Figure 2: ERP components P1, N1, and P3 at Pz.

rLRP The analysis of rLRP latency revealed a significant effect of search type, $Fc(1,10) = 5.15$, $p = .047$, but no effect of size, $Fc(1,10) = 0.31$, $p = .589$, and no interaction, $Fc(1,10) = 0.09$, $p = .772$. The mean latencies are shown in Table 2(d).

The rLRP component has been useful for contrasting the time-course of response for partial versus complete, or consistent versus inconsistent information (Coles, Gratton, & Donchin, 1988). If the responses designated to opposing hands are associated with different sources of information, then the ipsilateral from contralateral subtraction average, after counterbalancing for response sides, eliminates activity from processes common to both types of response, leaving activity that is specific to their differences. In our case, the competing sources were target (contralateral response) versus distractor (ipsilateral response) information. The interpretation of the difference depends on the underlying process of response selection. Supposing the speed of response is influenced by the discriminability between competing choices, then response selection will be longer in the inefficient search conditions. The situation is more complicated here, because of potential competition both between and within visual fields, in the set size four conditions. Regardless of the underlying response mechanism, though, it is clear that response selection is a contributing factor to search efficiency.

General discussion

The analyses of the previous section identified a number of significant differences in ERP components for efficient and inefficient visual search. A summary is provided in Table 3. Figure 3 shows the ERP components, P1, P2, P3, and rLRP and their temporal relationships for each condition. From this perspective several general characteristics of visual search efficiency emerge. First, P1, P2, and P3 onsets were similar across the four conditions. In terms of latency, there was no difference between efficient and inefficient search up to the engagement of working memory. Second, the differences between efficient and inefficient search arose during the execution of working memory, which in this case, we presume to include matching of input stimuli to the target. Third, the onset of response selection was later for inefficient than efficient search. We note that response selection appeared to partly operate in parallel with matching. Fourth, response selection took longer for inefficient than efficient search. Matching and response selection are the two component processes that contribute to the difference in response times for efficient versus inefficient search.

Table 3: Effects of type (T) and size (S), where $\overline{abc}$ ($\underline{abc}$) is an increase (decrease) in measure (• means no effect).

ERP	Site	Amp.	Lat.	Process
P1	Pz	$\overline{\text{S}}$	•	stimulus input
N1	Pz	•	$\underline{\text{S}}$	stimulus input
P2	Fz	$\underline{\text{T}}$, $\overline{\text{S}}$	•	selective attention
N2	Fz	•	•	selective attention
P3	Pz	$\underline{\text{T}}$	•	working memory
rLRP	C3/4	n/a	$\overline{\text{T}}$	response selection

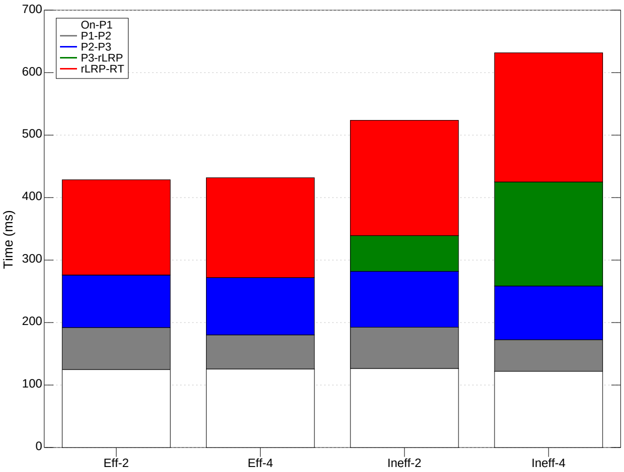

Figure 3: Onset latencies for P1, P2, P3 and rLRP.

Although our study was not designed to test a specific theory or model of visual search, the results do speak against the general two-stage framework that was the basis for the original Feature Integration theory (Treisman & Gelade, 1980). By this theory, visual features are first processed in parallel, then passed on to a second stage for serial processing of feature conjunctions. Thus, if the target is identifiable by a single feature, then search proceeds independently of the number of display items. Otherwise, each conjunction must be compared to the target separately, so response time is proportional to display set size. This two-stage framework predicts two distinct response modes (i.e., characterized by a relatively flat versus a relatively steep slope). Yet, a meta-analysis of response time data (Wolfe, 1998) failed to reveal a bimodal distribution of response time slopes. Our ERP results also do not support this sort of theory, where presumably there should be a difference between the onset of P3, and possibly P2 or N2, depending on how these components are supposed to correspond with the two stages.

The meta-analysis lended more support for a theory where features and conjunctions are processed within the same stage (e.g., Guided Search, Wolfe, et al, 1989), indicated by a unimodal distribution of response time slopes. For Guided Search, the first stage involves computing a noisy ranking of the similarity of each item to the target. The second stage involves matching the items to the target in rank order. But the processing stages are the same for feature or conjunction search. In terms of the distinction between selective attention (P2 and N2) and working memory (P3), our results are perhaps more compatible with the Guided Search model, where the early ERP components correspond to ranking the similiarity of each item to the target and P3 corresponds to matching each item to the target in order of rank. Assuming that ranking is a parallel process, then the onset of the earlier components will be the same across set type and size conditions. For Guided Search, response time is also determined by a serial process that matches each item to the target in order of similarity until a match is found. Interpreting P3 as an indicator of this matching process implies that onset will be the same across type and size conditions, but duration will be longer for inefficient search where the matching item is more likely to be further down the order.

In summary, selective attention (P2) based on feature information provides a fast mechanism for reducing the search space. But, unlike Feature Integration theory (Treisman & Gelade, 1980), it is not a complete route to target determination. Rather, it selects candidate items for subsequent matching to the target by working memory processes (P3). In the efficient (popout) conditions, though, typically only one item is selected, so matching and response selection may proceed independently of set size. Matching initiates response selection, at least partly in parallel. But, the time course of matching and selection depends on the number of competing items and their similarities. The onset of response selection may indeed coincide with the onset of matching, and inefficient search may include several intervening shifts of attention.

One potential confound with the effect of set type on P3 amplitude is a possible overlap with a slow negative wave from controlled search processes (see Kok, 2001, for a review). In this case, changes in P3 may reflect searching rather than matching processes. However, this interpretation does not explain why the onsets of P3 and earlier components did not change with search efficiency. A more likely explanation is that controlled search processes are interspersed between attempts by working memory processes to match items to the target, hence P3 amplitude was lower for inefficient search conditions, but P3 onset did not change.

The current results and analyses pertain to search efficiency over small sets within working memory capacity. Yet, we expect that they generalize to larger set sizes. How then do we reconcile the strong correlation between response time and P3 peak latency observed in other studies (e.g., Luck & Hillyard, 1990)? We think that P3 peak latency is a reflection of working memory duration, not onset. Larger sets may induce more intervening shifts of attention, and the subjective probability of targets may indeed be the cause of P3 peak variation. However, this cause is still compatible with our general claim that the onset of P3, indicating engagement of working memory processes, does not change with set type, or size.

The relationship between P3, search and memory can be tested more directly by contrasting ERP components in target-present versus target-absent conditions for feature versus conjunction search. Wolfe's meta-analysis also revealed that the ratio of target-absent to target-present slopes differed significantly between feature and conjunction search. In feature search, subjects terminated search in the absense of a target relatively earlier than for conjunction search, resulting in a smaller ratio. If P3 reflects the matching of items to a target in working memory, then we would expect no difference in P3 onset, but a longer duration for target-absent conditions, and that this difference would be greater for conjunction search.

Acknowledgments

We thank Eri Sugawara for assistance in collecting the data. This work was supported by a Grant-in-aid (19300092) from the Japanese Society for the Promotion of Science (JSPS). We also thank the reviewers for their thoughtful comments.

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