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Correspondence and requests for materials should be addressed to W.L. (e-mail: lutz@iiasa. ac.at).

Attentional requirements in a 'preattentive' feature search task

Julian S. Joseph*, Marvin M. Chun† & Ken Nakayama‡

** Department of Psychology, University of Nevada, Reno, Nevada 89557, USA*
† Department of Psychology, Yale University, New Haven, Connecticut 06520, USA
‡ Department of Psychology, Harvard University, Cambridge, Massachusetts 02138, USA

It is commonly assumed that certain features are so elementary to the visual system that they require no attentional resources to be perceived. Such 'preattentive' features are traditionally identified by visual search performance[1–3], in which the reaction time for detecting a feature difference against a set of distractor items does not increase with the number of distractors. This suggests an unlimited capacity for the perception of such features. We provide evidence to the contrary, demonstrating that detection of differences in a simple feature such as orientation is severely impaired by additionally imposing an attentionally demanding rapid serial visual presentation task involving letter identification. The same visual stimuli exhibit non-increasing reaction time versus set-size functions. These results demonstrate that attention can be critical even for the detection of so-called 'preattentive' features.

One basic tenet of modern vision research is that certain attributes of visual stimuli can be processed and detected in parallel across the visual field[4–6]. Visual attributes such as orientation[1,5,6], colour, or size differences[3] have been put forth as 'preattentively' perceived stimulus properties, a concept introduced by Neisser[4]. Perhaps owing to the emphasis on a dichotomy between 'preattentive' and 'attentive' processing, it is commonly assumed that attentional resources are not necessary for the perception of such image properties. This dichotomy stems from a long history of research with the visual search paradigm in which the time to detect a target is measured as a function of the number of display items (reviewed in ref. 3). Stimulus attributes that require focal attention to be perceived exhibit positive slopes: reaction times increase with increasing display size. In contrast, some search tasks show reaction times that remain flat or even decrease slightly as the number of items increases. Stimulus attributes leading to this behaviour, such as stimulus orientation, are thought to be processed in parallel across space with unlimited capacity; hence they are called 'preattentive' features, and are sometimes thought to be perceived without the use of attention. In the case of stimulus orientation, this fits well with the orientation selectivity of V1 neurons[7,8], which could conceivably permit the perception of orientation differences regardless of the attentional state.

If the perception of primitive features enjoys a special status in the visual processing stream, avoiding any bottleneck of limited resources, then performance in detection of a feature difference should be unaffected when attention is diverted elsewhere. We investigated the role of attention in the perception of 'preattentive' orientation features with a dual-task procedure as depicted in Fig. 1. We used a competing task, that of reporting the identity of a single white letter appearing in a rapidly changing stream of otherwise black letters at fixation. This rapid serial visual presentation (RSVP) is very demanding when presented at 12 letters s^{-1} and has been shown to effectively consume attentional resources for periods up to half a second[9]. A search array of oriented Gabor patches was presented for 150 ms, immediately followed by 150 ms high-contrast white-noise masks covering their locations. The lag between the onset of the white target letter in the RSVP stream and the onset of the orientation array was randomly varied to examine the temporal extent of interference, if any. In the single-task condition, subjects were instructed to ignore the letters and report only whether an orientation 'oddball', a uniquely oriented item, had been present. In the dual-task condition, subjects were instructed to report both the white letter and whether an orientation oddball was present.

Severe impairments in performance in detecting orientation oddballs resulted when the attentionally demanding RSVP letter identification was additionally imposed (Fig. 2). In the condition of performing only the single task of orientation oddball detection, subjects performed well, averaging 94% correct. However, when performing the dual task of letter identification and orientation oddball detection, oddball detection accuracy was only 60 ± 5% for simultaneous letter and orientation onset (lag 0). Note that the chance level of performance is 50% in this task. Significant degradation in performance persists for several hundred milliseconds after the target letter's appearance, as a result of the attentional demands for processing the target letter[9–11]. For the longest lag of 667 ms, dual-task performance recovered to the single-task level; thus the impairment reflects the temporal dynamics of attentional load rather than just a generic difficulty in encoding and retaining two independent responses. The effects of condition and lag, and the interaction between these variables were all significant ($P < 0.01$).

One might speculate that we observed attentional effects in the detection performance because these stimuli are unusual in some way and do not qualify as 'preattentive'. Performance was quite high when only the orientation oddball task had to be performed, but do these stimuli exhibit the standard experimental signature of so-called preattentive perception, specifically reaction times that do not increase with the number of items? There was no reason to expect otherwise, because many studies[1,3] have found this for orientation differences that are easily detected. Our stimulus display, however, was slightly different from those used in the usual visual search task in that our search array was on for only a short fixed duration and was masked, whereas it is more customarily presented without a mask and for a longer duration up to the time of the observer's response. To remove any residual doubts, we did a visual search reaction time experiment on visual stimuli that were precisely the same as those used in the first experiment, the only difference being that the number of oriented Gabor items was varied from trial to trial. Subjects were instructed to ignore the letters and respond correctly on the presence of a uniquely oriented item as rapidly as possible. The letter stream was presented as well, although

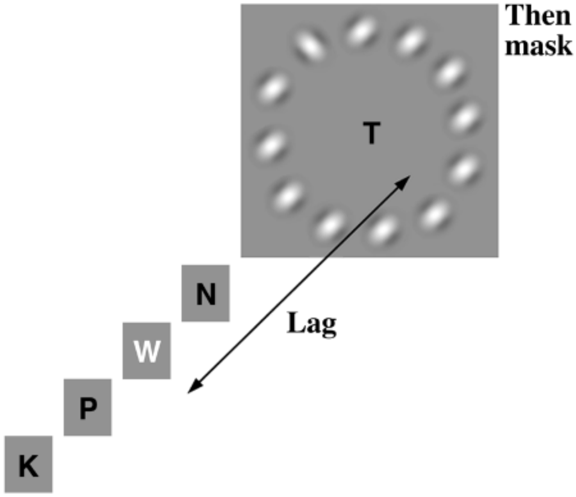

Figure 1 Schematic of visual stimuli. The Gabor items were oriented at either +45° or −45° with respect to vertical. Half the trials contained one uniquely oriented item (an oddball) and half contained no oddball (all items identical). Subjects responded whether an oddball was present. An RSVP stream of letters (36 arcmin tall) was concurrently presented at fixation. In some blocks of trials, subjects had to report the white letter in addition to responding whether an oddball was present in the circular array (dual-task condition). In alternating blocks, subjects ignored the letters and responded only as to the presence of an orientation oddball (single-task condition). Responses were not speeded; subjects were instructed not to make their keypress responses until after the display sequence was completed.

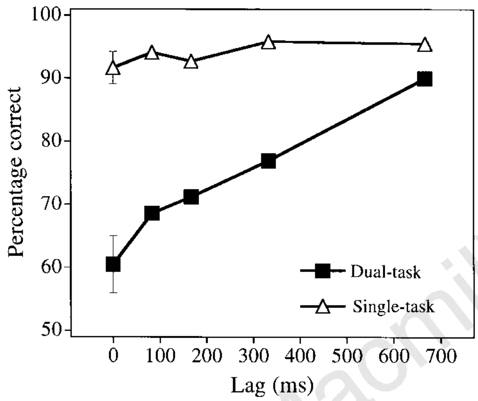

Figure 2 Percentage correct in the orientation oddball detection for the single-task (oddball detection only) and dual-task (letter identification and oddball detection) conditions as a function of the lag between the onsets of the target letter and the orientation array. Plots here and in subsequent figures represent the averages across subjects. Representative error bars indicate the s.e.m. across subjects. In the dual-task condition, the percentage correct in the oddball task was tabulated out of those trials in which the letter was identified correctly[9] (letter accuracy was 83%; chance was 3.8%).

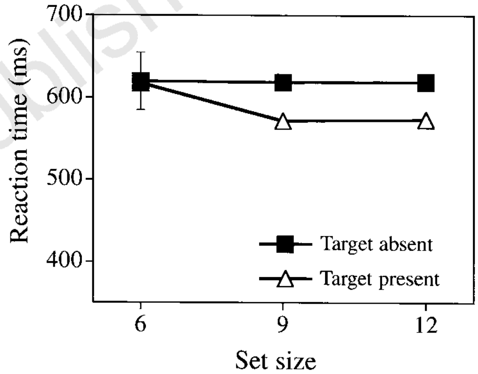

Figure 3 To check that the standard experimental signature of a preattentively perceived attribute was exhibited by our stimuli, we measured the detection reaction time as a function of the number of items in the display. The same stimuli were used as in the previous experiment, including the presentation of the letters, except that the number of oriented Gabor items was varied. Eight naive subjects each performed 10 blocks of 60 trials each, with oddball presence, distractor orientation, lag and set-size counterbalanced within each block. The reaction time for orientation oddball detection did not increase with the number of items in the search, which is characteristic of so-called 'preattentive' features. The error rate showed no set-size dependence and averaged 7%.

it was irrelevant to this task. Hence, on trials with set-size 12, the stimuli were physically identical in every respect to those used in the previous experiment.

The results (Fig. 3) show that the reaction time for detecting orientation oddballs does not increase with the number of distractor items. In fact, there is a slight decrease, which is to be expected from the higher density at the larger set-sizes. The perception of the same stimuli that displayed attentional requirements in the first experiment also exhibited the defining characteristic of a so-called 'preattentive' feature.

The circular arrays of oriented items discussed so far are the simplest way of studying the attentional requirements of detecting a feature difference, with each target and distractor having the same eccentricity and hence comparable visibility. One might imagine, however, that perception of an orientation difference within a two-dimensional array of items could conceivably be part of a qualitatively distinct class of visual tasks with no attentional requirements whatsoever. Such arrays were tested by Braun and Sagi[12,13] who found no diminution of performance in highly practised subjects using a task of discriminating between the letters L and T at fixation[13]. To explore this issue with the RSVP letter identification task, we examined the detection of orientation differences in two-dimensional arrays of 36 oriented Gabor items (Fig. 4a) essentially identical to those used by Braun and Sagi[12], but with increased contrast (53% instead of 36%) and with longer Gabor duration (33 rather than 20 ms). A Gabor-mask stimulus onset asynchrony (SOA) of 200 ms was used. In all other respects the procedure was the same as in the first experiment. Profound attentional impairment was again observed (Fig. 4b) with the same qualitative pattern. The greatest impairment was at the shortest lag times after the target letter. We repeated this experiment with six different naive subjects for an SOA of 133 ms and stimulus duration 100 ms, obtaining the same effects (Fig. 4b). We also replicated Braun and Sagi's null result with the L/T discrimination task at a variety of orientation stimulus SOAs after subjects had received extensive practice in each single task and the dual task, although there was an effect in the initial blocks that quickly decreased as the tasks were learned. These observations suggest that extensive practice can greatly reduce the observable attentional effects, although the use of different attentional tasks, RSVP letter identification compared with L/T[13,14]

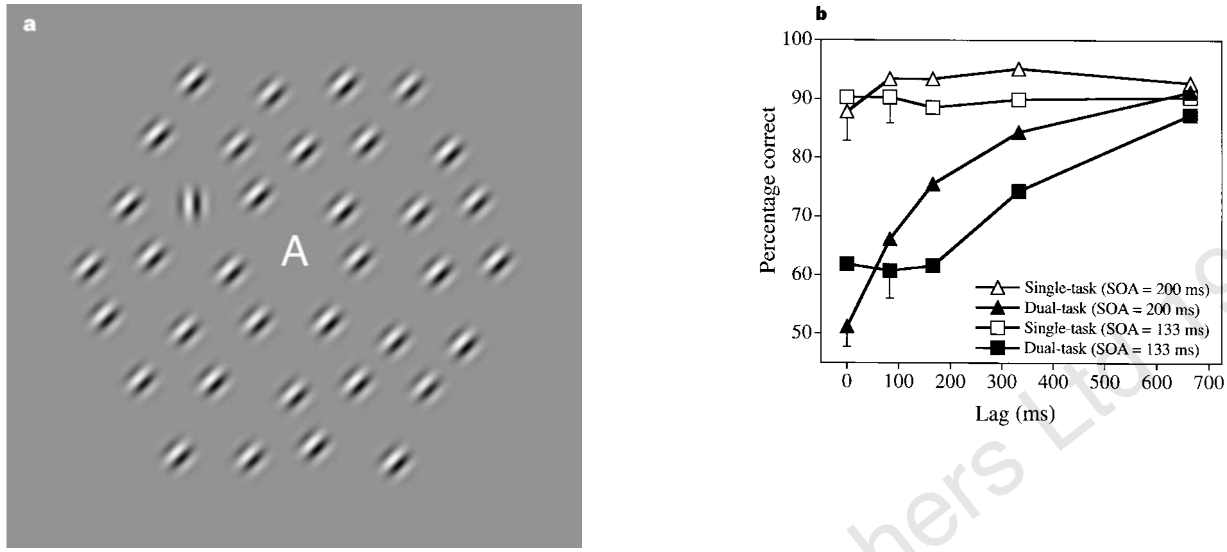

Figure 4 a, Two-dimensional array of oriented Gabor items used to demonstrate that similar performance impairments occur in the perception of this type of orientation difference. An orientation oddball, when present, was equally likely to appear in any location of the second concentric ring in the hexagonal array. The 33 ms array was followed by a 167 ms blank interval and a 100 ms array of masking elements consisting of superimposed high-contrast Gabor items of different orientations[12]. Six naive subjects were tested in both single-task and dual-task conditions, as in the first experiment. The same stimuli were tested on another six subjects with an SOA of 133 ms and a stimulus duration of 100 ms. **b**, In the two-dimensional arrays, detection of orientation differences was impaired by the attentionally demanding letter identification task (letter accuracy 76% and 75% respectively for the 200 and 133 ms SOA experiments). The effects of condition and lag, as well as the interaction between them, were all significant in each experiment ($P < 0.001$).

discrimination, might also have been partly responsible for the different results obtained in the present work.

In sum, our results show that visual feature search tasks, which have been deemed independent of attentional resources, are impaired by a sufficiently demanding attentional load. We demonstrated that both flat reaction time vs set-size functions and rapid discrimination performance are dissociated from unlimited-capacity detection of such 'preattentive' features. These findings seem to rule out a conceivable architecture for the visual system[4–6,12,13] in which all feature differences are processed along a pathway that has a direct route to awareness, without having to pass through an attentional bottleneck. The results are consistent, however, with the theoretical notion[15] that all tasks are contingent upon the availability of limited resources, while differing in their sensitivity to reductions in these resources. This view is supported by the results of Mack *et al.*[16,17], in which the presence of an otherwise salient object in the visual field frequently goes unnoticed when it is unexpected and irrelevant to the task at hand. In the present study, however, subjects are inherently constrained by limited attentional resources, even when actively interrogating the visual stimulus for the presence of a feature difference. These experiments argue against a direct route from preattentive processing to perceptual report. By providing a demonstration of 'preattentive' information that cannot be overtly perceived without attention, we challenge the current dichotomous view that assumes the existence of a separate privileged category of preattentive perception.

Methods

In the first experiment, six naive subjects, recruited for pay from the university community, each performed a 1-h session consisting of six blocks alternating between the single-task and dual-task conditions, with the order counterbalanced across subjects. Each block contained 80 trials, counterbalanced for the presence of an orientation oddball, distractor orientation and lag. Fourteen letters were presented after the target letter; between five and ten letters preceded it. No letter was repeated in a single trial. Luminances were 50 cd m^{-2} for the white letter, 7 cd m^{-2} for the black letters, and 25 cd m^{-2} for the background. Each letter in the stream was presented for 33 ms followed by a 50 ms blank gap. The Gabor functions were composed of a gaussian envelope with 50% peak contrast and a standard deviation of 22 arcmin, with a cosine modulation of 110 arcmin wavelength. The Gabor items were regularly spaced around a circle at 5.3° eccentricity, with a random overall phase in the locations of the array. Stimuli were binocularly viewed from a distance of 57 cm. Each trial began with a small dot appearing at fixation for 500 ms, followed by a 500 ms blank interval and the beginning of the RSVP letter stream. Subjects were first shown frozen displays, and then given 20 trials of practice in each the single-task and dual-task conditions with feedback in the first 10 before the experiment began.

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Correspondence and requests for materials should be addressed to J.S.J. (e-mail: jsj@unr.edu).