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Raised visual detection thresholds depend on the level of complexity of cognitive foveal loading

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Abstract. The objective of the study was to measure the interactions between visual thresholds for a simple light (the secondary task) presented peripherally and a simultaneously performed cognitive task (the primary task) presented foveally.

The primary task was highly visible but varied according to its cognitive complexity. Interactions between the tasks were determined by measuring detection thresholds for the peripheral task and accuracy of performance of the foveal task. Effects were measured for 5, 10, 20, and 30 deg eccentricity of the peripherally presented light and for three levels of cognitive complexity. Mesopic conditions (0.5 lx) were used.

As expected, the concurrent presentation of the foveal cognitive task reduced peripheral sensitivity. Moreover, performance of the foveal task was adversely affected when conducting the peripheral task. Performance on both tasks was reduced as the level of complexity of the cognitive task increased. There were qualitative differences in task interactions between the central 10 deg and at greater eccentricities. Within 10 deg there was a disproportionate effect of eccentricity, previously interpreted as the 'tunnel-vision' model of visual field narrowing. Interactions outside 10 deg were less affected by eccentricity. These results are discussed in terms of the known neurophysiological characteristics of the primary visual pathway.

1 Introduction

Sensitivity to a simple light stimulus is considerably reduced in the peripheral compared with the central retina (eg Johnson et al 1978; Weymouth 1958). This retinal inhomogeneity holds for both photopic and mesopic conditions and is said to be due primarily to the geographic distribution of rod and cone photoreceptors (Curcio et al 1990), and the variation in receptive field organisation across the retina (Banks et al 1991; Croner and Kaplan 1995; Drasdo 1977; Lee 1996).

Investigations of the visual field are based largely on the use of purely sensory tests, which are designed to minimise distractions, and allow observers to concentrate on the area in the peripheral visual field being tested. However, peripheral retinal sensitivity has been found to be compromised when attending to two visual tasks at the same time (Ambler and Finklea 1976; Bouma 1973; Chan and Courtney 1993; Holmes et al 1977; Ikeda and Takeuchi 1975). As a consequence, peripheral sensitivity may be reduced as the amount of information the subject is required to process is increased (Mackworth 1965; Rantanen and Goldberg 1999; Sanders 1964; Webster and Haslerud 1964). This results in an effective narrowing of the visual field.

The term 'functional visual field' (FVF) has been used to distinguish such cognitive measures of visual field sensitivity from the simpler sensory measures. It is defined as the spatial area or visual field that is needed for a specific visual task (Mackworth 1965; Sanders 1964) and indicates that peripheral sensitivity depends not only on retinal eccentricity, but also on the amount of information present in the visual field at the moment the target is being detected or identified. This notion of a labile visual field implies that a central mechanism controls the flow of information from the eye

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to the perceptual centres in the cerebral cortex. This mechanism allows the field to approach its physiological limits under optimal, uncluttered conditions, or forces it to contract when excessive central information is being processed.

Since the early reports of Mackworth (1965), it has been apparent that the peripheral sensitivity loss associated with a cognitive distracting stimulus may or may not vary with eccentricity. In some cases (Holmes et al 1977; Leibowitz and Appelle 1969; Webster and Haslerud 1964) there appears to be a uniform loss of sensitivity, largely independent of eccentricity, which increases with cognitive task complexity. These observations are explained in terms of a *general interference* model of dual-task interactions. On the other hand, the induced sensitivity loss may increase disproportionately with eccentricity, referred to as the *tunnel-vision* model (Bouma 1973; Chan and Courtney 1993; Engel 1971; Mackworth 1965; Sanders 1970). This model has also been referred to as a zoom-lens model of attentional effects (eg Eriksen and Murphy 1987).

One complicating factor, identified by Williams (1982, 1988), is that early studies supporting the tunnel-vision model confounded visual and cognitive complexity in their definition of mental workload (eg Ikeda and Takeuchi 1975; Mackworth 1965; Sanders 1970). Thus, Williams (1988) used a paradigm in which foveal visual factors were held constant, by using a character-classification foveal task and employing accuracy and reaction-time measures. Although his results did not provide overwhelming support for a tunnel-vision model (only a marginal interaction between foveal load and eccentricity was found), Williams concluded that increases in foveal cognitive load have a more detrimental effect on the processing of stimuli located several degrees of visual angle away from fixation, than on those located only one or two degrees from fixation.

As there are profound physiological differences between central and peripheral retino-cortical pathways and these lead to equally substantive functional differences (Drasdo 1991; Rovamo et al 1978), it may be that whichever of the two dual-task interaction models is valid depends on the nature of the peripheral task.

In the present study we measured the loss in peripheral sensitivity, which was the secondary task, induced by foveal mental workload, which was the primary task. A simple measure of peripheral sensitivity was used—detection of a flashing light. In our case the mental workload was visually presented. Others (eg Rantanen and Goldberg 1999; Webster and Haslerud 1964) have used an auditory-based loading task.

Previous studies have been confined to high (photopic) luminance levels and only a limited range of eccentricities. Therefore, their results reflect mainly cone function. It is well known that vision changes qualitatively under low and high luminance levels, and that, at least subcortically, different pathways operate depending on whether vision is rod- or cone-dominated (D'Zmura and Lennie 1986; Hood 1998; Lange et al 1997). Hence in the present study mesopic light levels were used in order to allow the operation of both classes of photoreceptors. We addressed the issue of uniformity of the task interactions by testing a wide range of eccentricities. This enabled us to determine unequivocally which of the two types of dual-task interactions holds.

In addition to the effect on the peripheral task, the possibility of a reciprocal effect was investigated by monitoring the performance of the foveal task. This enabled us to ensure that the correct relative priority of the two tasks was maintained. It also provided control of the quality of fixation and the level of vigilance in the foveal task.

2 Methods

2.1 *Subjects*

A total of five adults (three males and two females), with a mean age of 25.8 years (range: 21 to 32 years), served as subjects. The subjects were optically corrected and their visual acuity was better than 6/5. The subjects viewed the stimulus through natural pupils and monocularly (right eye). All subjects were right-handed.

2.2 *Apparatus*

A slightly modified Goldmann–Weekers adaptometer (Haag Streit AG, Ophthalmological Instruments, Switzerland) was used to obtain luminance thresholds. A digital spotmeter (Photo Research 1500, Micron Techniques Limited, California) was used to calibrate the adaptometer, so the data from the raw records could be converted to candelas per square metre. The test field was a white light from an incandescent lamp (colour temperature 2250 K) which was viewed through a diffuser. The test field was surrounded by a matt-black cone of low reflectance giving a zero-luminance surround. The ambient illuminance level was 0.5 lx and was uniform in the room.

2.3 *Stimulus characteristics*

The test field subtended 1 deg. It was placed at four different eccentricities on the temporal retina (right visual field). Eccentricities up to 30 deg were used.

The foveally presented display unit (HPDL-1414 model, Hewlett Packard), which consisted of large, easily discriminated, red LED numeric characters, was mounted on a card at a viewing distance of 41 cm. The digits (all numeric characters from 0 to 9) were displayed in pairs, adjacent to each other, subtending 0.4 deg $\times$ 0.3 deg (2.85 mm $\times$ 2.1 mm) and were separated horizontally by a gap subtending 0.33 deg (2.35 mm) (see figure 1). The display unit was driven by a PC, which allowed a range of presentation durations of the digits.

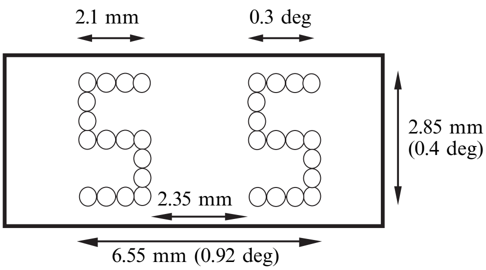

Figure 1. The LED display unit used as the foveal task for the experiment. Note that the characters are highly visible subtending 0.4 deg $\times$ 0.3 deg. Sketch not to scale.

2.4 *Experimental design*

The repeated-measures design contained two independent variables. Temporal retinal eccentricity (5, 10, 20, and 30 deg) and foveal load (four levels: no load, low load, medium load, high load) were manipulated within subjects. Each subject contributed 96 observations (16 conditions $\times$ 6 determinations) in a test session. Trials were run in four blocks (for the four eccentricities) of 24 observations each with a 5-min rest period between blocks. Since five subjects were tested, there were 30 observations per cell in the experiment.

During the experiment, the computer recorded the foveal task performance by counting the number of correct and total responses. Each subject contributed about 100 to 150 responses to the foveal task for each condition (the total number of responses varied for each subject/condition, depending on their response time—see below). The percentage of correct responses over total responses was used as an estimation of foveal performance. This was assessed for five different levels of retinal eccentricity (no peripheral task—NPT, and 5, 10, 20, 30 deg) and three levels of foveal load (low, medium, high).

2.5 *Procedure*

During a 10-min adaptation period to the mesopic (0.5 lx) illumination, the instructions were read to the subject. The subject was seated at the dark adaptometer with his/her chin resting on a chin-rest. The importance of steady fixation was emphasised. Subjects were specifically informed to give priority to the foveal task over the peripheral task. Fixation was monitored by the experimenter. Accuracy of performance for the foveal task was computed and this provided a secondary control of eye movements, because subjects were continuously responding to the appearance of the foveal task with a key-press (see session 4). The threshold for the detection of the flashing light was measured by the method of adjustment.

Note that only the mental workload of the foveal task was manipulated. Its visual complexity (two highly visible digits) remained constant for the different load levels. In the no-load (control) condition the subject simply fixated on the LED digits without responding to them. In the low-load condition, the LED characters randomly changed with a constant exposure duration and the subject responded with a key-press using the index finger of the right hand on the down arrow key each time the number changed. In the medium-load condition, the subject pressed the down-arrow key of the computer keyboard each time a low ($\leqslant 4$) number was displayed and did not respond when a high ($\geqslant 5$) number was displayed. In the high-load condition two different digits were displayed simultaneously (see figure 1) and the subject pressed the left arrow key if the left digit was numerically greater, or the right arrow key if the right digit was the greater.

Each subject had a 20-min practice session (responding to the foveal task without the presence of the peripheral one) prior to the main experiment in order to become familiar with the equipment and procedure. Also, during this warm-up period, an exposure duration of the LED digits was determined for each subject corresponding to at least 90% correct responses for the most difficult (high-load) task. This would be employed throughout the test trials for the subject. Exposure durations varied between 700 and 950 ms for the different subjects.

3 Results

Two measures of performance were used in these experiments. Foveal task accuracy, in terms of percentage of correct responses, was monitored whilst detection thresholds to the peripherally presented target were obtained. Primarily we were interested in the link between the cognitive complexity of the central task and the loss of sensitivity to the peripheral task. There was, however, a reciprocal effect, in that the accuracy of the cognitive task was reduced when thresholds were set for the peripheral task. The data for the performance of the foveal task are described first.

3.1 *Foveal accuracy*

Mean accuracy scores (percentage of correct responses) as a function of the three levels of foveal task load (FL) and retinal eccentricity (RE) of peripheral task are shown in table 1. An analysis of variance (ANOVA) on these data, that included FL and RE as factors, revealed a significant effect of FL ($F_{2,72} = 50.74$, $p < 0.001$) and a significant effect of RE ($F_{4,70} = 7.59$, $p < 0.001$). However, the interaction between FL and RE was at the threshold of statistical significance ($F_{8,60} = 2.00$, $p = 0.062$). The implications for this are considered in section 4.

Table 1. Mean foveal accuracy scores (percentage of correct responses) and standard deviations (in parentheses) for five subjects as a function of foveal task load and retinal eccentricity of the peripheral task. In the 'no peripheral task' column the foveal accuracy scores were recorded in the absence of the peripheral task.

Foveal task load	Eccentricity of peripheral task/deg				
	no peripheral task	5	10	20	30
Low	100.0 (0.0)	99.7 (0.7)	99.2 (1.1)	99.1 (1.2)	99.1 (1.0)
Medium	98.0 (2.0)	95.2 (2.8)	90.3 (6.6)	92.4 (3.8)	89.5 (6.6)
High	96.0 (3.7)	88.8 (5.2)	83.1 (4.5)	82.2 (7.7)	83.7 (7.6)

Scheffé a posteriori comparisons showed that there was a highly significant difference in foveal task accuracy among the three FL conditions ($p < 0.001$) (see figure 2). There were no significant differences in foveal accuracy between the four eccentricities (5, 10, 20, and 30 deg) of the peripheral task. However, there were significant differences between the no-peripheral-task (NPT) condition and the 10, 20, and 30 deg eccentricity conditions (all p values < 0.004). Note, as is evident from figure 2, that there were differences between the NPT condition and 5 deg eccentricity, but these did not reach statistical significance ($p = 0.35$).

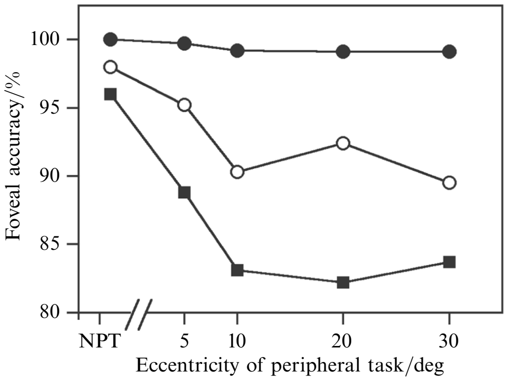

Figure 2. Mean foveal accuracy (percentage of correct responses) as a function of the eccentricity of the peripheral task (and in the absence of the peripheral task, NPT) for the three levels of foveal overload (low: filled squares; medium: open circles; high: filled circles). See table 1 for standard deviations.

In figure 2, mean foveal accuracy is plotted as a function of the eccentricity of peripheral task for the different levels of foveal task load. The link between foveal accuracy and the eccentricity of the peripheral task is obvious. It is clear that the concurrent presentation of the peripheral task at any eccentricity causes a detrimental effect on the performance of the medium-load and the high-load foveal task, but not the low-load task. It is also evident from this figure that, when the peripheral task is placed at 5 deg, the decrease in foveal accuracy is less than at the other eccentricities. Beyond 10 deg, foveal accuracy is largely independent of peripheral task eccentricity. Hence, the main point in figure 2 is that any eccentricity effects are confined to the central 10 deg.

3.2 *Peripheral detection thresholds*

Figure 3 shows plots of detection thresholds (means and SDs) versus foveal task difficulty for the range of eccentricities tested and for all subjects. The data show that there is an elevation in detection thresholds with both increasing eccentricity and foveal task load. As might be expected, there are quantitative differences between subjects' thresholds, but overall the pattern of effects is repeated for all subjects. For this reason, scores of normalised detection threshold (threshold/minimum threshold) were obtained prior to statistical analysis. Minimum threshold was assumed to be the threshold at 5 deg, when no foveal task was required, ie no-load condition. Mean normalised threshold values as a function of foveal task load and retinal eccentricity are shown in table 2.

Table 2. Mean normalised thresholds and mean standard deviations (in parentheses) for five subjects as a function of eccentricity of the peripheral task and foveal task load.

Eccentricity/deg	No task	Low task load	Medium task load	High task load
5	1.0 (0.1)	1.3 (0.2)	1.7 (0.3)	1.7 (0.3)
10	2.1 (0.3)	3.8 (0.8)	5.6 (0.7)	6.2 (0.7)
20	5.4 (0.9)	9.2 (1.6)	15.6 (2.5)	22.2 (4.2)
30	28.0 (7.0)	61.5 (15.8)	101.6 (29.9)	118.0 (28.2)

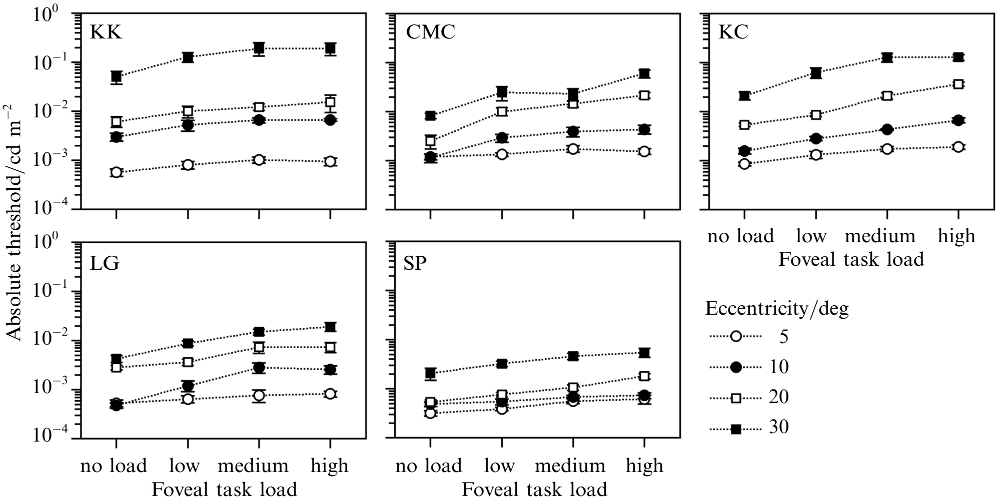

Figure 3. Absolute detection thresholds as a function of foveal task load and eccentricity of peripheral task for all five subjects tested. Each data point represents the mean of six readings and the error bars ±1 standard deviation.

In figure 4, mean (across subject) normalised detection thresholds plotted on a logarithmic scale are shown as a function of retinal eccentricity of the peripheral task for the four foveal load levels used. It is evident that the effect of foveal loading on detection thresholds at 5 deg eccentricity is relatively small. That is, at this eccentricity, whether no-load or high-load conditions were used did not greatly influence sensitivity to the peripheral task. At 10, 20, and 30 deg, however, there are quite large differences in sensitivity between the four levels of cognitive load.

A two-factor ANCOVA was performed on these data (normalised log detection threshold scores) with retinal eccentricity (RE) of the peripheral task used as a covariate (this is justified because it is known, a priori, that detection thresholds increase with eccentricity at the light levels used) with foveal task load (FL) and subjects as factors. The RE main effect was highly significant ($F_{1,19} = 5911$, $p < 0.001$). Moreover, significant effects of FL ($F_{3,16} = 20.68$, $p < 0.001$), FL × RE ($F_{3,16} = 18.25$, $p < 0.001$) and of subjects × RE interaction ($F_{4,15} = 113.0$, $p < 0.001$) were found. There were no other subject-specific interactions (all p values > 0.18). Note that the FL × RE interaction implies a tunnel-vision effect.

It is apparent from figure 4 that, for small visual angles ($\leqslant 10$ deg), the sensitivity loss induced by the cognitive loading increases rapidly with eccentricity—what has

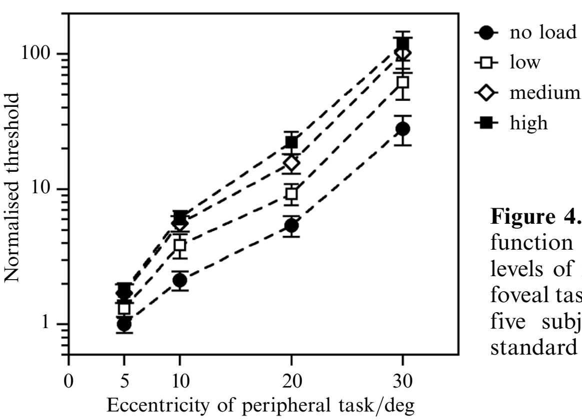

Figure 4. Normalised detection thresholds as a function of retinal eccentricity for the various levels of foveal task load and in the absence of a foveal task. Each data point represents the mean of five subjects and the error bars the mean of standard deviations.

been described as a tunnel-vision model of dual-task interactions. For eccentricities greater than 10 deg, thresholds do increase with eccentricity, but the interaction between foveal load and retinal eccentricity is less pronounced. In other words, the cognitive load effects were more uniform with eccentricity, suggesting a general interference model applies (see section 4).

As far as the influence of the foveal task difficulty is concerned, Scheffé a posteriori comparisons showed that there was a significant effect of normalised log detection thresholds among the four load conditions ($p < 0.001$). As can be seen in figure 4, the effect of load increase was greater between no, low, and medium foveal load than between medium and high loads.

4 Discussion

The experiments described provide strong evidence that peripheral sensitivity to a simple light is reduced when combined with a foveal, cognitive task and that the extent of the sensitivity loss is linked to the degree of complexity of the cognitive loading. In addition, the accuracy of the cognitive task is significantly compromised by the performance of the peripheral task.

4.1 *Effect on peripheral thresholds*

The data address previous arguments on the characteristics of the reduced FVF under conditions of increasing foveal task complexity (Chan and Courtney 1993; Mackworth 1965; Rantanen and Goldberg 1999; Sanders 1970; Williams 1982, 1988). Statistical analysis revealed an interaction between FL and RE under the experimental conditions used in this study. However, as might be anticipated from the characteristics of the visual pathway, there appears to be a kind of 'division of labour' between the central 10 deg and the rest of the peripheral field. This effect is evident in figure 4—the increase in threshold caused by the foveal load between 5 and 10 deg is much greater than that between 10 and 20 deg or between 20 and 30 deg. This disproportionate increase in threshold is consistent with the tunnel-vision model of simultaneous information processing. The effect of conducting the foveal task—the difference between no load and high load—appears to be less dependent on eccentricity beyond 10 deg, suggesting that here a general interference model operates.

This study extends the investigation of interactions between foveal loading and peripheral target perception in two ways. First, in order to investigate the possibility that different regions of visual field may process information in qualitatively different ways, we have tested a wide range of eccentricities. Previous experimenters used mostly identification tasks which fall precipitously with eccentricity and as a result they have tested only the central 10–15 deg (eg Bouma 1973; Chan and Courtney 1993; Holmes et al 1977; Ikeda and Takeuchi 1975; Mackworth 1965; Sanders 1970; Williams 1988). Hence, they could not show any differences in threshold–distractor interactions between the central 10 deg and more peripheral locations. We were able to test a relatively wide range of eccentricities because mesopic conditions were used, thus encouraging the operation of rods, which dominate in the periphery (Curcio et al 1990).

Second, in our experiments the peripheral task is simple. Instead of involving identification or discrimination of complex characters as in many studies (see above), observers set absolute detection thresholds for the peripheral target. Letter recognition is known to be perceptually complicated (Westheimer 1992), whereas the detection of a light is comparatively simple and is almost certainly limited by retinal mechanisms. The simplicity of the peripheral task is an important feature of these experiments. It addresses the issue whether foveal loading affects *any* peripheral task or only those which involve high-level visual processing. There are many studies which have shown that peripheral vision is specialised for detection not recognition (Johnson et al 1978;

Kelly 1984). Hence, it is not surprising that the effect of the foveal load is particularly pronounced in the central 10 deg for our simple detection task.

This finding is consistent with the underlying neurophysiology. Human vision has a strong foveal bias. It is known from anatomical (eg Wässle et al 1990) and psychophysical (Drasdo 1977; Rovamo et al 1978; Virsu et al 1987) studies that the cortical representation of the fovea occupies a large area, whilst the peripheral visual field claims only a small portion of the visual cortex. In the presence of such a disproportionate allocation of neural resources, it is reasonable that the foveal task interferes more with the peripheral task when the latter is presented within 10 deg, than at greater eccentricities. Furthermore, it is well known that the visual pathway in higher primates is composed of two classes of neurons referred to as magno (M) cells and parvo (P) cells after the layers in the lateral geniculate nucleus (LGN) to which they project (see for example Lee 1996). It is likely that these two pathways have different values for cortical magnification (Drasdo 1991). In the present experiments we have used simple detection thresholds and low light levels, so our measurements will be dominated by M-cell activity.

In other studies more complex tasks have been used. Rees et al (1997) measured the effect of a linguistic distractor on sensitivity to the motion aftereffect. They showed reduction in motion processing despite the distractor being unrelated to the primary task. This implies that a central mechanism operates across modalities. This is not a new idea. Mackworth (1965) speculated that the contraction of the useful field of view prevents system overload.

An additional point on the eccentricity effects concerns the possibility that either eye movements or subject response bias might have affected the results. Subjects were instructed to fixate steadily on the cognitive task and their eye movements were monitored by the experimenters. One could argue that eye movements could account for the eccentricity effects, because subjects would be more likely to make eye movements at the greater eccentricities. In fact, it is highly improbable that subjects could have made any type of eye movements whilst they were continuously responding to the appearance of the foveal task with a high rate of correct responses. In support of this, May et al (1991) found that the range of spontaneous eye movements in a free-viewing primary task decreased as cognitive workload increased.

As far as response criteria changing for different eccentricities are concerned, this is difficult to control by the method of adjustment. It could be that subjects were more conservative at the greater eccentricities. However, this would result in stronger effects at the periphery. As all subjects demonstrated a similar pattern of results, it seems highly improbable that our findings are due to eccentricity-specific response bias.

Finally, there is also evidence that practice in the tasks used in these types of studies improves the ability to detect peripheral targets under dual-task conditions (eg Engel 1971; Ikeda and Takeuchi 1975). Experiments have shown that experienced aviators (Williams 1995) and drivers (Crundall et al 1999; Roenker et al 1997) have a less restricted FVF compared with their less experienced colleagues. Attentional effects have also been reported for elderly observers. In the present experiments all subjects were young. Certainly, it is well known that there is a strong age effect on the FVF, indicating that elderly observers are particularly prone to attentional deficits under challenging conditions (eg Ball et al 1988; Korteling 1994; Madden 1990; Plude and Hoyer 1985).

4.2 *Reciprocal link between the two tasks*

So far we have emphasised the effect on peripheral thresholds of performing a foveal task. In figure 2 we present strong evidence of the opposite effect: performance of the foveal task declines when responding to the peripheral target. This effect varies with the cognitive complexity of the foveal loading as might be expected and it is highly statistically significant (see table 1). Crucially for the interpretation of these data, if the peripheral task is absent, performance of the foveal task is minimally affected by the different levels of loading (see figure 2). When the peripheral task is introduced, the low loading has no effect on performance whilst the other two loads have a dramatic effect.(1) Because the visual complexity of the task is the same for the three loading conditions this is powerful evidence that only the cognitive element influences the interaction between the two tasks.

A second point relates to the effect of eccentricity. Again, the interactions between these two quite different tasks—one purely visual the other purely cognitive—are stronger within the central 10 deg of the visual field than they are outside this region. In fact, this so-called tunnel-vision effect is even more compelling for these data than for the peripheral threshold data: when the peripheral task is conducted at eccentricities beyond 10 deg there is little or no effect of eccentricity. Our interpretation of this is similar to the equivalent observation on the peripheral task—it points to the qualitative differences in information processing between central and peripheral visual fields.

4.3 *Concluding remarks*

In describing some characteristics of the central mechanism, which controls the allocation of visual attention, this study highlights some interesting additional questions. For example, in showing strong interactions between sensitivity to a simple light, presented peripherally, and conducting a central cognitive task [which does not necessarily require visual fixation; Rantanen and Goldberg (1999) used an auditory task] we have raised the central issue whether foveal loading would influence the performance of any peripheral task. It is likely that the effects found may vary with the nature of the peripheral task and the physiological characteristics of the neurons mediating the response. One might speculate that the more primitive visual tasks, such as flicker and simple detection, would be relatively immune to foveal-loading interactions, whereas the phylogenetically more recently acquired visual abilities, such as visual acuity and colour vision, would be highly susceptible to these effects.

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