CORTICAL CONTRIBUTIONS
TO THE
AGE-RELATED DECLINE IN
CONTRAST SENSITIVITY

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by

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SUMMARY

A signal detection paradigm was employed to investigate the possibility that changes in decision-making may contribute to the age-related decline in contrast sensitivity. Detection of sinusoidal grating patterns was measured at 3 and 15 c/deg for a range of contrasts which were psychophysically equivalent for young and old subjects. A decline in contrast sensitivity with age at the spatial frequencies studied was confirmed for contrast thresholds obtained both by an ascending method and from the 50% hit rate for detection of the grating pattern. The criterion adopted for decision-making, expressed as both β and percentage bias, did not change significantly between young and old subjects at 15 c/deg. At 3 c/deg, criterion did not change significantly at 0.8x, 1.0x, or 1.2x contrast threshold, but at contrast giving 50% hit rate there was a significant increase with age. Paradoxically, the percentage bias increased significantly at contrast threshold but not at 50% hit rate. It is inferred from the results that the loss of contrast sensitivity is not accountable in terms of adoption of a more conservative criterion by older subjects. Hence visual loss in ageing is attributed to changes within the visual pathway rather than within higher decision-making centres.

In order to further investigate this conclusion, the transient pattern visually evoked response (PVER) was recorded in young and old subjects to the onset of a vertical sinusoidal grating pattern of spatial frequency 3 and 8 c/deg and contrasts 40%, 20%, 10%, 5% and 3%. The waveform evoked contained a series of negative and positive components which were labelled N1, P1, N2 and P2. The latencies of the N1, P1 and N2 components were generally found to be significantly longer in old subjects compared with young, while no significant age-related differences were found for P2. Amplitudes and rise times were not found to be significantly different between the age groups. Latencies of the first 3 components generally generally showed a significant inverse correlation with log contrast although the 'gain' of the relationship was not significantly different between young and old subjects. Amplitude and rise time showed no significant correlation with log contrast. The age-related latency changes were confirmed when PVERs to grating patterns of 40% contrast and spatial frequencies 1, 2, 3, 5, 8, 10 and 15 c/deg were recorded in young and old subjects. The latencies of N1 and P1 were found to be significantly correlated with increasing spatial frequency. Rise times of P1 and N2 were significantly inversely correlated with spatial frequency. Amplitudes of P1 and N2 showed a significant inverse correlation with spatial frequency only in young subjects.

Age-related latency changes in the flash VER are interpreted in terms of a possible decline in cortical inhibitory function in old subjects.

PVERs were also recorded to grating patterns of 3 and 8 c/deg, the contrasts of which were normalized with respect to contrast threshold and hence were psychophysically comparable between subjects of different ages. At 8 c/deg there were no significant latency, amplitude or rise time differences between young and old subjects. At 3 c/deg, however, the age-related latency differences were maintained, even though the stimuli had been made perceptually equivalent.

The results indicate that the location of at least some of the physiological changes underlying the age-related deficit in visual performance must lie in or prior to the primary visual cortex where the early components of the PVER are thought to be generated.

In addition, it is concluded that the results in the signal detection experiment where contrast thresholds obtained from the 50% hit rate at 3 c/deg (but not 15 c/deg) were higher than expected in old subjects, and the results in the PVER experiments where normalizing stimulus contrast failed to abolish age-related latency differences at 3 c/deg (but not 8 c/deg), can best be explained by an impairment in old people in the processing of transient stimuli at low spatial frequency.

GENERAL INTRODUCTION

MEASURES OF VISUAL PERFORMANCE

Visual performance is often taken to be synonymous with visual acuity, the latter typically being measured using the familiar letter chart introduced by Herman Snellen in 1882 and now in widespread use in ophthalmology. Many factors can influence visual acuity but perhaps the most pervasive - and certainly the most inevitable - are those changes which accompany ageing. A number of studies have shown that visual acuity declines with age (reviewed by Weale, 1975, 1982). For example, Anderson and Palmore (1974) found that, while almost 60% of subjects in their 60s had acuity of 6/6, only 14% of subjects aged 80 or over had a similar acuity measurement. These results, obtained from a cross-sectional comparison, were confirmed by longitudinal data collated over a 10 year period from subjects initially aged 60 or over; in these subjects, acuity became progressively worse over the period of the study. In a review paper, Weale (1975) concluded that visual acuity in fact begins to fall above the age of 45 years resulting in an 80% loss over the subsequent four decades.

The Snellen chart consists of an array of letters arranged in rows of progressively smaller size. The subject, viewing from a standard distance (usually 6 metres), reads as far down the chart as possible until no longer able to identify the letters. An individual's performance is graded relative to the performance of a subject with normal eyesight. The test is useful, quick and easily implemented. However, it has a number of drawbacks: for example, the task involves recognition of letters and hence there is the possibility that the subject might either confuse similar letters or obtain identification cues from markedly different letters, both instances affecting acuity measurements. An alternative acuity test, developed by Hans Landolt in 1889, requires the subject to indicate the position of a gap on a circle - the smallest detectable break in the circle being the measure of acuity. This test bypasses some of the problems with the Snellen chart i.e. differences in culture and literacy should have little influence on performance.

These tasks have in common the fact that they measure the smallest detail which the subject is capable of identifying. For the most usual form of ophthalmological examination, where the patient's best optical correction is being measured, such indicators of visual acuity are often adequate. However, acuity is merely an indication of the subject's ability to resolve fine detail and does not necessarily provide any information about the manner in which he or she might perform over the full range of object sizes. It is apparent that the ability of a subject to perceive a stimulus will be influenced by the contrast of that stimulus. Conventional measures of acuity (such as the Snellen test) typically use only relatively high contrast targets.

CONTRAST SENSITIVITY

A psychophysical test with which to better characterize spatial vision is the *contrast sensitivity function* first measured by Schade (1956). This is the plot of the subject's contrast sensitivity (the inverse of his or her contrast threshold) against spatial frequency. It describes the ability of the observer to see, in terms of minimum required contrast, objects or stimuli of varying sizes. Most often the stimulus used in the experimental determination of contrast sensitivity is a vertical sinusoidal grating pattern - a display of alternating light and dark bars, usually generated on an oscilloscope or television monitor, the luminance distribution across the screen being described by a sine wave. In this context, object size is analogous to spatial frequency, i.e. the number of repeating units of the pattern (one cycle - a dark and a light bar) per degree of visual angle. Patterns of a low spatial frequency (containing 'wide' bars) correspond to coarse detail or objects of large size; patterns of a high spatial frequency (containing 'narrow' bars) correspond to fine detail or objects of small size.

There have been many studies investigating the manner in which contrast sensitivity varies with spatial frequency. Typical findings in normal young subjects have indicated that the relationship is bell-shaped, with the curve having a fairly well-defined peak (maximum contrast sensitivity) at between 2-4 c/deg and that on either side of this peak there is a fall-off with both decreasing and increasing spatial frequency (Campbell and Robson, 1964; Campbell and Green, 1965; Virsu, Lehtio and Rovamo, 1981). In young subjects, the high frequency cut-off point (i.e. the highest spatial frequency which could be perceived) has been observed to be around 35 c/deg, corresponding to a Snellen acuity of 6/5 (McGrath and Morrison, 1981).

Various factors can influence the amplitude and shape of the contrast sensitivity function. For instance, a reduction in mean retinal luminance moves both the peak of the curve and the high frequency cut-off point to lower spatial frequencies (Patel, 1966), while defocus causes a reduction in sensitivity to high spatial frequencies (Campbell and Green, 1965). If the grating is flickering then sensitivity is enhanced at low spatial frequencies (Kulikowski and Tolhurst, 1973). Sensitivity is highest when the pattern is oriented vertically, less so when it is horizontal, and lowest when the orientation is oblique (Campbell, Kulikowski & Levinson, 1966). The number of cycles constituting the grating pattern is another important influence on contrast sensitivity: if fewer than about eight bars are present then the low frequency fall-off in sensitivity is more pronounced (Hoekstra, van der Groot, van den Brink and Bilsen, 1974).

VISUAL SYSTEM AS SPATIAL FREQUENCY ANALYSER

A large body of evidence now suggests that the visual system can detect spatial frequencies independently of each other and that the processing of this information occurs through the action of multiple channels differentially responsive to particular ranges of spatial frequency.

Evidence that such a multi-channel system operates in humans comes largely from psychophysical studies. Pantle and Sekuler (1968) found that exposing an observer to a grating pattern of a particular spatial frequency temporarily reduced the sensitivity (i.e. increased the contrast threshold) for similar gratings. The same findings were reported by Blakemore and Campbell (1969) who found a fivefold increase in threshold after prior exposure to high contrast gratings of the same or similar frequency. The effect was restricted to a range of frequencies centred on the adapting frequency and with a bandwidth of just over an octave at half amplitude. At higher adapting frequencies (above 14 c/deg) the bandwidths were slightly narrower; at lower adapting frequencies (below 3 c/deg) the peak of the effect remained at 3 c/deg. The sensitivity changes were orientation specific.

Adapting to a grating pattern not only affects an observer's threshold but also his or her perception of gratings at suprathreshold contrast levels. Gratings of a higher and lower spatial frequency than the adaptation grating will appear higher and lower respectively than they really are, the effects not being apparent at the adapting frequency nor at frequencies more than two octaves away (Blakemore, Nachmias and Sutton, 1970). In addition, at adapting frequencies below 3 c/deg the effect remains centred at 3 c/deg and becomes less potent as the adapting frequency is lowered.

Graham and Nachmias (1971) suggested that if the multiple channel model was correct then detection of a complex pattern containing two superimposed sinusoidal gratings of frequency F and 3F should occur only if the contrast in at least one of the components is at or above threshold for that component presented alone. By altering the phase and contrast of both components this was indeed found to be the case.

Although these channels are often taken to be independent, Tolhurst and Barfield (1978) found that when the test frequency differed from the adapting frequency by one to two octaves, threshold was lowered, perhaps indicating a release of inhibition on 'surrounding' channels when one channel is fatigued.

Spatial frequency 'uncertainty effects' in the detection of grating patterns have been cited as providing further evidence for multi-channel models of frequency perception. The detectability of a sinusoidal grating is reduced when it is intermixed in a series of trials with gratings of other spatial frequencies (Davis and Graham, 1981). The tuning of the uncertainty effect became sharper if a grating of any one particular spatial frequency was predominant in the run of trials e.g. the effect was smaller for frequencies near that frequency than for those further away.

Electrophysiology has also contributed evidence substantiating the multiple channel theory. In the visual system of the cat, spatial frequency sensitive neurones have been discovered which respond selectively to grating patterns within specific bandwidths (Maffei and Fiorentini, 1973) and with an optima covering the entire range of the contrast sensitivity function (Campbell, Cooper and Enroth-Cugell, 1969). From the optic tract, through the lateral geniculate nucleus to the simple cells in the visual cortex there is a progressive narrowing of the response bandwidth of the cells in question (i.e. the neurones become more finely tuned). Complex cortical cells are less finely tuned than the simple cells. For the latter type and for some complex cells there is a linear relation between the amplitude of the response (the proportional change in frequency of firing) and the logarithm of grating contrast (Maffei and Fiorentini, 1973). In humans, masking (as indicated by a reduction in evoked potential amplitude) is greater when the masking pattern used is similar to the stimulus eliciting the electrical response, e.g. a grating of similar spatial frequency (Musso and Harter, 1975).

Campbell and Maffei (1970) found that stimulating with a grating containing two spatial frequencies (8Hz pattern reversal) caused an increase in the slope of the regression line of PVER amplitude against stimulus contrast only if the frequencies used were far enough apart (about one octave separation). This increase in slope steepness was interpreted as indicating the activation of two separate channels.

It has been further suggested that the visual system carries out its processing of the visual world in a manner which might be amenable to interpretation in terms of Fourier analysis (Campbell and Robson, 1968). *Detection* thresholds for different grating patterns have been shown to be determined only by the fundamental Fourier component of the waveform. However, *discrimination* between differing patterns becomes possible only when contrast has exceeded the threshold of higher harmonic components. A sine wave and a square wave of the same fundamental frequency will have the same detection threshold but will be indistinguishable from each other at that contrast level. At very low spatial frequencies, however, the threshold of the first harmonic will be lower than that for the square wave fundamental itself (since the harmonic will be of a frequency nearer to the peak of the contrast sensitivity function). This means that discrimination between square and sine wave *will* be possible at detection threshold (Green, Corwin and Schor, 1981).

If this method of analysis were that used by the visual system then one might expect that adapting to a square wave grating would reduce subsequent sensitivity not only to a sine wave grating of the same fundamental frequency but also to a sine wave grating of a frequency three times that of the first Fourier component (a square wave grating can be considered as being made up of sine waves of frequencies F, 3F, 5F etc, having amplitudes which are inversely proportional to their frequency). Hence the third harmonic component present in the square wave should itself cause adaptation in its associated spatial frequency channel given that the nervous system performs this type of analysis on visual information. This has indeed been found to be the case; Blakemore and Campbell (1969) found that adaptation to a square wave grating produced a reduction in sensitivity in the region of the third harmonic frequency suggesting that different spatial frequency channels carry out independent analysis of the harmonic components constituting the square wave stimulus.

Similar conclusions were drawn by Carpenter and Ganz (1972) who also used an adaptation paradigm. Two tasks were involved: in one, the subject had to detect the presence of a 1 c/deg square wave grating; in the other, had to decide whether two 1 c/deg square wave gratings were aligned or not. The most effective adaptation for the first task was found to be a 1 c/deg sine wave grating (since, in this instance, the threshold of the square wave fundamental was more important than that of the higher frequency harmonics). For the second task the best adaptation was a 3 c/deg sine wave grating (since the threshold of the third harmonic component - edge information - was of greater importance).

DeValois, DeValois and Yund (1979) tried to determine the relative effectiveness of grating and checkerboard patterns in terms of their stimulatory effects. They made single-cell recordings from simple and complex striate cortex cells in the cat and found that the best orientation for a checkerboard pattern was one which was dependent on the Fourier components (the fundamental runs diagonally across the pattern) rather than the orientation of the edges.

However, Nachmias, Sansbury, Vassilev and Weber (1973), in a modification of Blakemore and Campbell's (1969) experiments, found no evidence to suggest that the visual system operates in such a manner. A 3 c/deg adapting square wave grating had no effect on the contrast threshold for a 9 c/deg grating whereas a 9 c/deg adapting grating (same frequency as the third harmonic component of the square wave) increased the threshold for the test grating by 0.2 log units.

It has been further suggested that different processing mechanisms operate at high and low spatial frequencies; a distinction drawn on the basis of preferential sensitivity to stationary and moving patterns (Tolhurst, 1973). At low spatial frequencies the best adapting stimulus is one which is moving; when a stationary adapting pattern is used then only slight adaptation occurs (Tolhurst, 1973). Breitmeyer (1975) has claimed that his results from reaction time experiments in which increasing spatial frequency of the grating stimulus caused an increase in simple reaction time (even when contrast was matched across the range of spatial frequencies used) provide psychophysical evidence for the existence of transient and sustained channels, the former operating at low spatial frequencies, the latter at high spatial frequencies. The terminology used is intended to suggest correspondence with the two types of functionally distinct pathways from retina to lateral geniculate nucleus discovered, using electrophysiological techniques, in the cat (Cleland, Dubin and Levick, 1971). The justification for employing the same terms as Cleland et al is that transient ganglion cells have a larger receptive field than their sustained counterparts (i.e. 'prefer' low spatial frequency stimulation) and respond only at the onset and offset of a stimulus. Vassilev and Mitov (1976) similarly found that reaction time increased with spatial frequency. This was found to be the case even when a high and a low spatial frequency stimulus (9c/deg and 3c/deg) were presented at psychophysically equivalent contrasts.

One problem with the conclusions drawn from these reaction time studies is that the discontinuity that one might expect to see in the curve of reaction time against spatial frequency, given that a different mechanism is operating at each end of the frequency spectrum, is not present in either of the above sets of results. This objection is not critical, however, since the area of 'overlap' between the two systems is substantial (Kulikowski and Tolhurst, 1973) and hence might mask the exact crossover point. Although Parker and Salzen (1977a) could find no electrophysiological indication of such a shift (i.e. no sign of an early evoked potential component disappearing leaving a later one), Jones and Keck (1978) observed that at stimulus spatial frequencies below 3 c/deg an additional early positive component did appear, perhaps indicating the activation of the transient system.

Tolhurst (1975) found that reaction times to near-threshold high spatial frequency gratings were distributed throughout the stimulus presentation whereas RTs to lower spatial frequency gratings were grouped after any sudden change in the stimulus (i.e. at onset or offset). The fact that Vassilev and Strashimirov (1979) recorded visually evoked 'OFF' responses only with low spatial frequency gratings, never with high, is consistent with Tolhurst's (1973) transient / sustained classification.

EFFECTS OF AGE ON CONTRAST SENSITIVITY

Attempts to specify the way in which the contrast sensitivity function varies with age have produced differing results. Arden (1978), using the printed gratings which he himself developed (with spatial frequencies extending from 0.2 to 6.4 c/deg), observed no changes in visual performance with increasing age (11-70 yrs), although he failed to mention whether or not subjects were appropriately corrected. Employing the same method, Skalka (1980) found that advancing years were accompanied by a worsening in performance, the deterioration being apparent from the second decade onwards but becoming more dramatic (the fall-off slightly steeper) in the fifth decade. Similar results (reduced contrast sensitivity with age) were also obtained using Arden gratings by Sokol, Domar and Moskowitz (1980).

Arundale (1978) used gratings generated on television, an improvement on the Arden gratings which can be prone to experimenter effects. The patterns used by Arundale had spatial frequencies varying from 0.25 to 28 c/deg. In the oldest age group (45 to 66 yrs) the contrast threshold was lowest at 2 c/deg compared with 4 c/deg in the group aged 18 to 39 yrs. The contrast sensitivities of the two groups were comparable at low spatial frequencies (below 0.5 c/deg) but at medium and high spatial frequencies the old group was less sensitive. In this study, however, the low number of subjects in the old group (N=5) precludes generalizing from these results with any confidence.

Sekuler and Hutman (1980) and Sekuler, Hutman and Owsley (1980) compared contrast sensitivity in two groups of subjects (mean ages 18 and 73 yrs). They found that at 16 c/deg (the highest spatial frequency used) both groups showed similar sensitivities. At low and medium spatial frequencies the elderly subjects showed diminished sensitivity, requiring at the 0.5 c/deg frequency three times as much contrast to see the gratings as did the young subjects (gratings were phase-reversed at either 0.3Hz or 6Hz). However, these findings are rendered suspect by the fact that the subjects were not optimally refracted.

Vaegan and Halliday (1982) found that the age-related contrast sensitivity reduction at or below 3.2 c/deg was not present when a forced choice paradigm was used. Owsley, Sekuler and Siemsen (1983) also found that age had no influence on sensitivity at low spatial frequencies (1 c/deg or less) but that at higher frequencies (up to the 16 c/deg used) contrast sensitivities were reduced, the effect manifesting itself at around 40 - 50 yrs. The peak of the curve was also affected, shifting from 4 c/deg in young subjects to 2 c/deg in old subjects (in their sixties). They attributed the disparity with their earlier results (no age change at 16 c/deg) as being possibly due to the fact that the previous group of subjects had been matched for visual acuity

(20/30 or better) and hence might have been expected to perform comparably at higher spatial frequencies (acuity can be regarded as analogous to the highest frequency perceivable).

Kline, Schieber, Abusamra and Coyne (1983) used gratings of spatial frequencies from 0.5 to 12 c/deg and found that old subjects (mean age 64.4 years) were less sensitive than young subjects (mean age 18.3 years) at intermediate and higher frequencies (young women were found to be more sensitive than their male counterparts whereas in old age there were no sex differences). In a study using a wider range of spatial frequencies (0.5 to 40 c/deg), Derefeldt, Lennerstrand and Lundh (1979) found that the old subjects (over 60 yrs of age) had lower contrast sensitivities than did young subjects (aged 20 to 40 yrs), although the reduction was only at a significant level between 5 and 40 c/deg ($p<0.01$). Similar findings were made by Ross, Clarke and Bron (1985): there was a significant decrease in contrast sensitivity with age for the four contrast sensitivities tested between 2.88 and 19.23 c/deg. For the two lower spatial frequencies tested - 0.4 and 0.95 c/deg - the reduction, although present, was not significant.

In the study on Alzheimer's disease carried out by Schlotterer, Moscovitch & Crapper-McLachlan (1984), the contrast sensitivity curve of normal old subjects (53 - 77 yrs) was shifted downwards in comparison with that of normal young subjects (20 - 29 yrs). This applied across the range of spatial frequencies tested (0.5 - 12 c/deg) and was most apparent at the higher spatial frequencies. Similar results (a downward shift in the curve with age, accentuated at the highest spatial frequency tested) were reported by Wright and Drasdo (1985).

McGrath and Morrison (1981) investigated contrast sensitivity across a wide range of spatial frequencies. The subjects were aged from 5 to 94 yrs. The position of the peak of the curve was found to be unaffected by age but contrast sensitivity was reduced at all spatial frequencies, the greatest loss occurring at medium frequencies (the curve peak - 2-6 c/deg). Up to about 50 years of age the upper frequency limit (the highest frequency which could be perceived and hence a measure of visual acuity) stayed constant; above this age there was a marked decline (dropping from about 35 c/deg in young subjects to around 15 c/deg in subjects in their 70s).

In summarising previous studies: visual performance, as assessed by contrast sensitivity, declines over a wide range of spatial frequencies with age, the reduction tending to be most apparent at the high frequency limb of the contrast sensitivity function.

EFFECTS OF AGEING ON THE VISUAL SYSTEM

Although the age-related decrement in visual performance is undisputed, there is still much uncertainty and controversy about the anatomical location of the physiological changes which underly the psychophysically measured functional decline.

The processing of visual information can be regarded simplistically as consisting of four different stages:

(i) transmission of image by *ocular media*
(ii) reception and transduction by *retina*
(iii) transmission and processing by *retino-geniculo-striate pathway*
(iv) integration and decision-making by *higher centres*

At each of these stages a number of age-related physiological changes occur which may (or may not) contribute in varying degrees to the observed decline in visual performance.

Ocular media

The first stage in the chain of visual information processing is the optical system of the eye: those components which, functioning optimally, provide the best possible image for transduction by the retina. In many individuals the optics do not function optimally and in old people especially there are a number of physiological changes which do occur and which could be regarded as possible candidates for the locus of the observed functional changes. It is well known that the eye's ability to accommodate for near vision is progressively reduced with age (e.g. Brückner, 1959). This *presbyopia* means that an old person will be unable to focus an object at as close a distance to the eye as would a young person. The loss of accommodative power with age can be accounted for by changes in the elastic properties of both the lens substance and capsule and by an overall flattening of the lens (Fisher, 1973). These particular changes can be counteracted by the wearing of spectacles with positive lenses of appropriate power. However, even thus corrected, visual performance in the elderly is still reduced compared with that of the young.

A possible explanation for this is *senile miosis*, the reduction in pupil diameter which accompanies advancing years. Altering the size of an aperture can influence the resolving power of an optical system. Decreasing pupil diameter will reduce the effects of geometrical aberrations since the light will pass exclusively through the centre rather than the periphery of the lens. At small pupil diameters (2.0 to 3.0 mm) this advantage is counterbalanced by the deleterious effects of diffraction (Campbell and Green, 1965). Birren, Casperson and Botwinick (1950) photographed 222 eyes of subjects ranging in age from 20 to 89 years. They found a reduction in pupil size with increasing age: in the third decade the mean pupil diameter was 5.11mm while in the ninth decade the mean diameter was 3.42mm; in the dark-adapted eye the mean diameter was 7.42mm and 4.87mm respectively. Kadlecová, Peleska and Vasko (1958), measuring the pupil diameter of 453 normal subjects after 15 minutes dark adaptation, made similar measurements: approximately 7mm in subjects in their 20s; approximately 5mm for subjects in their 70s.

It may be the case that the smaller pupil diameters of older subjects might at least partly account for the changes in visual performance. Although a smaller aperture is advantageous in that less light scattering will occur and refractive errors will be of less importance, the associated reduction in retinal illumination might contribute to the age-related visual deficits (at age 60 the retinal illumination is surmised to be one third that of the 20 year old eye; Weale, 1961). It has often been shown that optimal visual performance is dependent on the amount of light entering the eye. Campbell and Gregory (1960) investigated how variations in pupil size affected resolution of a grating pattern. At high luminances a 2mm artificial pupil was optimal whereas at low luminances a 7mm pupil was more appropriate. Woodhouse (1975) concluded that optimum size of artificial pupil corresponded very closely with the natural pupil size at different levels of illumination.

Reduced pupil size is more common in elderly subjects. However, it seems unlikely that it contributes in any significant way to the age-related decline in contrast sensitivity. Morrison and McGrath (1985) found no difference in the contrast sensitivities of a group of young subjects when viewing with a natural 8mm pupil or through an artificial 3mm pupil. Reducing the retinal illumination by viewing through a 0.5 log unit neutral density filter also had no discernible effect on the contrast sensitivity of young subjects. In a study which compared the spatial contrast sensitivity under different luminance levels of young subjects (ages 20 to 33 years) and old subjects (67 to 79 years), Sloane, Owsley and Alvarez (1987) found that simulating senile miosis by the use of artificial pupils could not completely account for the observed reduction with age of contrast sensitivity. Kay and Morrison (1987), in quantifying the effects of varying pupil diameter on the contrast sensitivity of young subjects (aged between 18 and 40 years), found that changes in pupil size (between 2 and 8mm and achieved using a range of artificial pupils over eyes dilated with homatropine) had a virtually negligible effect on sensitivity (the exception being for the smallest diameter which significantly reduced sensitivity at 0.5 and 1 c/deg.)

Although senile miosis appears to have been exonerated as the major cause of the age-related reduction in visual performance there is, of course, another contributor to the reduction in retinal illumination in elderly people. The crystalline lens undergoes a number of changes as the individual ages: the cortex becomes thicker as new cells are added (the nucleus staying relatively constant) while the nucleus, cortex and capsule all become more dense (Niesel, 1982). The lens becomes yellow in appearance as its optical density increases (Said and Weale, 1959).

The lenticular yellowing and thickening must affect both the quantity and the quality of light reaching the retina (less blue light is passed) but is this enough to account for the documented changes in visual performance? In fact, there is much evidence to suggest that it is not. Measuring the transparency of post-mortem lenses by immersing them in castor oil and projecting through them gratings of various spatial frequencies in order to determine the finest resolvable pattern, Weale (1983) found that there was no significant variation in transparency with age (between 32 to 80 years). In a study which attempted to mimic experimentally the degrading effects of cataract (simulated by smearing varying quantities of petroleum jelly onto a lens) Zuckerman, Miller, Dyes and Keller (1973) showed that up to 40% cataract (defined as per cent of lens surface covered thus) had little effect on target contrast. For a larger object (18.4 min arc as compared with 1.15 min arc) a 'cataract' of 80% severity still passed satisfactorily.

Vaegan, Bank and Gathy (1987) found that colour vision losses due to lenticular yellowing did not become apparent until the eighth decade (the reduction in contrast sensitivity which they observed occurred from the sixth decade onwards).

Another means by which to investigate the optical quality of the human eye is that developed by Campbell and Green (1965). This method involves projecting interference fringes directly onto the subject's retina using a helium-neon laser, and comparing the contrast sensitivity function obtained using this method with that obtained using externally-viewed gratings generated on an oscilloscope. By calculating the ratio of the two contrast sensitivity functions it is possible to determine the optical quality. With themselves as subjects, Campbell and Green

(1965) found that, although the sensitivity using the laser gratings was always the higher of the two (due to the fact that it bypassed the optics and any deteriorating effects which they might have), the high frequency fall-off in sensitivity could not completely be accounted for in terms of optical degradation of the image, since the fall-off observed using the laser gratings was steeper than the fall-off in the contrast ratio (optical quality).

Using the same technique with subjects of different ages, Morrison and McGrath (1985) were able to demonstrate that even in elderly subjects (up to 86 years) the optical quality was still good enough to provide an image on the retinal surface more than adequate for the resolving power of the retina / brain. A predominance of neural effects was a conclusion also reached by Elliot (1987) who used a similar technique to the above. In order to assess the effects of wide angle scattering, Morrison and McGrath (1985) also included a comparison of the visual performance of normal aged subjects with that of old subjects who had undergone removal of a cataractous lens and were either aphakic or had received a perspex lens implant. In these subjects, contrast sensitivity to the laser interference fringes were comparable to those of normal age-matched subjects. This showed that the decline in visual performance must arise in some subsequent stage of the visual system (i.e. in the retina or beyond).

Owsley, Gardner, Sekuler and Lieberman (1985) drew the same conclusion in their comparative study of elderly phakic and aphakic eyes; a group of 10 old subjects (mean age 70 years) who had undergone cataract extraction and lens insertion were found to have contrast sensitivities which were not significantly different from those of 11 normal subjects (mean age 71 years) with a non-cataractous crystalline lens.

Jay, Mammo and Allan (1987), using Snellen acuity as their index of comparison, similarly found no significant differences between normal elderly eyes and those in which an acrylic lens had been implanted. The decline in visual performance with age was the same in both operated and unoperated subjects.

Finally, Ponte, Anastasi and Giuffre′ (1987) measured visual evoked potential latency to checkerboard stimulation in normal elderly subjects up to 80 years with no ophthalmic diseases or lens opacities and with a visual acuity of 0.8 (20/25) or better; their results were compared with those from a group of aphakic elderly subjects with similar corrected acuity (≥0.8). There were no significant latency differences between the two sets of subjects.

Taken together, the physical, psychophysical, and electrophysiological evidence serves to indicate that the locus of the changes underlying the age-related decline in visual functioning must lie not in the optics of the human visual system but at some subsequent level of the information processing chain.

Retina

Weale (1986) pinpoints three possible ways by which the process of ageing can manifest itself in the retina: (i) random cell death, (ii) blood-borne influences, and (iii) phototoxicity or other environmental effects.

One problem in this area is the fact that it is difficult to separate the effects of normal age-related physiological changes from those brought about by the pathological changes which can often, though not always, be apparent in elderly people. Indeed, the problem is more profound since categorising an age-related effect as physiological rather than pathological presupposes that the former is a consequence of normal ageing and the latter that of abnormal changes which, although associated with the ageing process, are not direct or necessary results of ageing *per se*. This supposition may not be well-founded. For example, senile macular degeneration is often regarded as an age-related pathology - however, given the numbers of individuals affected by the condition (one survey showed 30% of women between the ages of 75 to 85 years to be affected (Weale, 1986)) it might be argued that it is more appropriate to regard the syndrome as a normal, rather than a pathological, consequence of ageing.

Nevertheless, even disregarding those conditions considered to be disease-related, there are still many deleterious factors with which the ageing retina is faced. The vascular system undergoes changes which, though not necessarily specific to the retina, can have profound effects on visual function. Arteriosclerosis associated with arterial narrowing and, more seriously, by artery and vein occlusion can lead to profound blindness. Less dramatic are changes such as a reduction in capillary volume and a decrease in corpuscle numbers (Weale, 1982).

It has been suggested that light itself can have a cumulative deleterious effect on the retina; a lifetime's exposure to the continual photic bombardment has been postulated to ultimately result in receptor malfunction. In the normal young eye, receptor damage or waste products can be dealt with through phagocytosis by the pigment epithelium; it has been proposed that in the older eye this 'debris removal system' might be less effective, perhaps resulting in incomplete phagocytosis of damaged photoreceptors and an accumulation of toxic substances such as free radicals leading to cell dysfunction and ultimately to cell death (Marshall, 1978).

A non-invasive method of investigating retinal function involves the use of the electroretinogram or ERG, the electrical potential recorded by a corneal electrode when the retina is exposed to light. The ERG contains two major components: the a-wave is associated with photoreceptor activity; the b-wave is believed to be generated in the inner nuclear layer. It is generally found that increasing age is accompanied by a decrease in the amplitudes and an increase in the latency of both these ERG components (Weleber, 1981; Wright, Williams, Drasdo and Harding, 1985; Birch and Fisch, 1988; Porciatti, Falsini, Scalia, Fadda and Fontanesi, 1987). Although these results can be interpreted as representing changes in retinal cell functioning it is true to say that their significance is still unclear.

A more direct assessment of age-related retinal changes involves the histological examination of eyes removed during surgery or after death. Several such studies have shown that a number of morphological changes occur in the human retina and are correlated with increasing age. Gartner and Henkind (1981), in a histological examination of eyes aged 3 to 96 years, found that above 30 years and with increasing age the photoreceptor nuclei showed an increased displacement from the outer nuclear layer into the outer plexiform layer; above 40 years there was an increased incidence in the number of nuclei displaced from the outer nuclear layer to the layer of the rods and cones. Also above the age of 40 years, 24 of the 104 eyes examined showed reductions both in the number of photoreceptors in the macular area and in the number of nuclei in the outer nuclear layer.

Human rods undergo morphological changes with age; in the fourth decade nodular protrusions become apparent on rod outer segments, initially in the perimacular region but in later years in an increasing number of rods and spreading to the entire retina. By the time the seventh decade has been reached the proportion of rod cells thus affected is 10-20% of the entire retinal population (Marshall, Grindle, Ansell and Borwein, 1979). Electron microscopy shows that the swellings revealed under the light microscope are in fact caused by the outer segments becoming folded back upon themselves, the convolutions so formed appearing under low magnification as nodular excrescences. In some instances the boundary membrane of the outer segment can become fused to the area against which it has become folded

(Marshall et al, 1979). Grindle and Marshall (1978) report that advancing age is associated with an increasing disorder in cone outer segments; by the time the eighth and ninth decades are reached the outer segment membranes are in a condition of great disorganization. In the same study, which looked at 73 human retinae ranging in age from 19-90 years, pigment epithelial cells were found to contain the greatest amounts of lipofuscin deposition in eyes obtained from patients in their mid-40s or older. A more recent study looked at the macular, equatorial and peripheral retina and found in all regions an increase with age of lipofuscin, melanolysosomes and melanolipofuscin. The prevalence of melanin granules was found to decrease with age as did the volume of unpigmented cytoplasm in retinal pigment epithelium cells (Feeney-Burns, Hildebrand and Eldridge, 1984). However, one interesting observation in this study was that teenage eyes contained equally high levels of lipofuscin, suggesting that the presence of the pigment does not necessarily ally itself with visual impairment.

Tucker (1986) noted an increased incidence of the presence of refractile inclusion bodies (membrane-bound organelles possibly produced by a process of autophagy) in cone inner segments in retinae from older human eyes (in approximately 68% of eyes above the age of 40 years compared with only 33% of eyes below this age).

Ordy, Brizzee and Hansche (1980) attempted to relate visual acuity and foveal cone density in the retina of the aged rhesus monkey - a species of primate with a visual system comparable to that of man. The animals were trained to discriminate between gratings of different orientation, and acuity thresholds were determined by establishing the finest target which they could perceive (set at an 80% correct discrimination rate maintained over a period of 3 consecutive days). Three age groups were compared: young (5 years), middle aged (12 years), and old (22 years); the acuity of the oldest group was found to be significantly less than that of the two younger groups (both of which had similar acuities). After death, morphometric measurements of foveal cone density were made - a significant decrease of 20% was found in the old group compared with young.

In humans, Sarks (1976) categorized 378 eyes into six different groups according to the amount of macular abnormality observed histologically (primarily in terms of the stage in the development of basal linear deposit under the pigment epithelium). The age range studied extended from 43 to 97 years, clinical ocular assessment being carried out in the months prior to death. Groups I and II consisted of tissue which Sarks regarded as being in a state indicative of the processes of normal ageing; groups III and IV showed the progressive effects of senile macular degeneration; groups V and VI were comprised of eyes showing the full effects of macular deterioration. Ageing changes were apparent even in the absence of any observable pathology; Bruch's membrane underwent thickening and hyalinization, the latter extending in some cases to the level of the outer boundary of the choroidal capillary network. Photoreceptors underwent changes: in group III some rods and cones appeared stunted; in group IV they became more distorted and in some places absent; in group V they showed progressive degeneration and atrophy and were reduced in numbers.

This study attempted to relate visual acuity (measured, on average, 16.4 months prior to death) with the histological appearance of the retinae obtained post-mortem. The subjects in group I category showed 6/6 vision in just over 50% of the cases (66/120), none of whom were above 80 years. The reason for the reduced acuity could not be accounted for by changes in the retinal morphology (and was ascribed instead to attention lapses or changes in the optical media).

A major problem with these histological studies is that they are unable to differentiate causal from correlative elements in the ageing process. Even those studies which do attempt to relate psychophysical results prior to death with histological information obtained post-mortem, are faced with the virtually impossible task of specifying the nature of the relationship between the observed sets of data; is it causal, correlative or coincidental? This problem applies not only to the retina but to subsequent levels of the visual system.

Retino-geniculo-striate pathway

The brain undergoes many structural changes (both fine and gross) as it ages. At the most superficial level, brain weight, which stays constant during the years of maturity, begins to fall from about the age of 70 onwards (Ordy, Kaack and Brizzee, 1975). A gross inspection of an aged brain shows clear evidence of atrophy of the gyri and widening of the sulci, shrinkage of both grey and white matter with an increase in ventricular space (Scheibel and Scheibel, 1975). The general vascular changes invoked as possible candidates for a causal role in retinal functional changes can apply equally well to the central nervous system. Cerebral blood flow has been shown to be reduced with increasing age (Melemed, Lavy, Bentin, Cooper and Rinot, 1980) although the cortical capillary system is apparently quite resistant to the effects of advancing years. Hunziker, Addel'al and Schulz (1979) found significant changes in capillary morphology (including increased diameter and decreased specific surface area) in the pre-central gyrus of the frontal lobe but only in brains aged between 65-74 (the age-range examined extended from 19 to 94 years). Gross examination of cerebral blood vessels (the Circle of Willis) indicated that age (from the fourth decade onwards) was manifested by an increase in opaqueness of vessel walls, an increased degree of 'cork-screwing' (twisting and turning) along the length of the vessel wall, and an increase in tubular resiliancy. The 'cork-screwing' effect was also apparent at a microscopic level (precentral and occipital cortex) as was the appearance of nodular outgrowths, end-bulbs and sinusoidal formations (Fang, 1976).

The electrical activity of the brain as assessed by the recording of the electroencephalogram (EEG) or the visually evoked response (VER) also shows changes in responsiveness with age (see VER Introduction).

At a histological level of examination, ageing is accompanied by an increase in the presence of lipofuscin, an intracellular fluorescing pigment, and in the appearance of senile plaques, conglomerations of degenerating axons and dendrites surrounding an amyloid core (Scheibel and Scheibel, 1975). The relationship between these structural changes and functional changes (e.g. intellectual impairment, memory loss etc.) is open to debate - for instance, while there appears to be some correlation between the incidence of senile plaques and the manifestation of senile dementia, their appearance seems to be neither necessary nor sufficient for the development of the illness (Scheibel and Scheibel, 1975).

The visual information, having undergone transduction by the photoreceptors, passes out of the retina through the optic nerve on its way, via the lateral geniculate nucleus, to the visual cortex. In ageing, a marked loss of optic nerve fibres (ganglion cell axons) is apparent. Johnson, Miao and Sadun (1987) concluded that there were significantly fewer fibres in old optic nerves than in young optic nerves (although there was a good deal of individual variation). Balazsi, Rootman, Drance, Schulze and

Douglas (1984) showed that in the optic nerve there was a loss of over 5,600 axons per year, amounting to a total of approximately 400,000 fibres during a 70 year life span. Dolman, McCormick and Drance (1980) also showed a general trend of axon loss with increasing age, the decrease becoming more apparent above 60 yrs.*

Cell numbers in the cortex also undergo quantitative changes: Brody (1955) made a histological examination of 20 brains at various stages of development, maturity and senescence (newborn to 95 years). He observed a steady loss of cortical neurons from age 20 onwards, in some areas (e.g. superior temporal gyrus, precentral gyrus, striate cortex) amounting to a 50% decrease in the total neuronal population.

Brody's counts correlated well with those obtained using the automated method of Henderson, Tomlinson and Gibson (1980) which showed a 35% loss of small neurons (<19 µm in diameter) and a 50% loss of large neurons throughout the life span.

At the level of the visual cortex, neuron population density in the macular projection area was measured by Devaney and Johnson (1980) in 23 brains aged between 20 and 87 years. A comparison of the youngest and oldest tissue samples showed that there was a greater than 50% reduction in neuron density with age (4.56×10^7 / gm in the 20 year old brain; 2.10×10^7 / gm in the 87 year old brain).

In addition to a decrease in cell quantity there are also qualitative changes in neuronal morphology which may contribute to the age-related functional decline. For example, in the human visual cortex the number of dendritic spines on pyramidal cells

* However, post-mortem loss of optic nerve fibres is known to be substantial (Balazsi et al, 1984) and hence may be confounding the above results.

has been observed to decrease with age (Scheibel, Lindsay, Tomiyasu and Scheibel, 1975). In the rat, membranous inclusions within the dendritic shaft become more prevalent with increasing age (Feldman, 1976).

The changes in function may have less to do with neuronal loss *per se* than with alterations in the biochemical status of the ageing brain. Samorajski (1981) points out that any modification, however slight, of neurotransmitter substances or associated enzymes may lead to an imbalance which could have detrimental repercussions on the processing of neural information. For instance, in the striatum and the hypothalamus it is known that with advancing age there is a marked decline in the catecholaminergic systems while the cholinergic and serotonergic systems do not change so rapidly or dramatically. In the normal ageing cortex there is a selective loss of cholinergic systems, similar in type, though not quantity, to that observed in senile dementia and Alzheimer's disease (McGeer and McGeer, 1980).

Various areas of the occipital cortex differ in the way in which age affects enzymic activity: area 19 (visual association area) shows a significant decrease in choline acetyltransferase (ChAc) activity, a reduction not paralleled in either area 17 (visual receiving area) or area 18 (around the calcarine fissure). The latter is characterised by an age-related decline in glutamic decarboxylase (GAD) activity not seen in the other visual areas. Acetylcholinesterase (AchE) levels stay relatively constant with age in all three of the above-mentioned occipital regions (McGeer and McGeer, 1976).

Higher centres

The term 'higher centres' is one characterised primarily by its vagueness - from the retina to the striate cortex (and near-neighbouring extra-striate areas) there appears to be a reasonably close relationship between the conceptual stages in the information processing chain and the anatomical stages in the signal transmission sequence. Beyond the occipital lobe it becomes more difficult to specify the manner in which structure and function are related. From the striate cortex, pathways lead to areas 18 and 19 and to other regions of the cortex (including the parietal, temporal, and frontal lobes) as well as to subcortical structures such as the lateral geniculate nucleus, the superior colliculus and the amygdala. Data concerning any age-related structural changes in these areas is marked by its paucity. Obviously, many or all of the age-related morphological changes which can affect earlier stages will have similar effects on higher levels; e.g. neurovascular modifications, cell loss, biochemical imbalance etc.

'Higher centres' can be regarded, in terms of a functional definition, as those areas concerned with higher-order integration of information and with cognitive manipulation and evaluation of this information (in order to decide upon the appropriate and best response). In this respect, there is much evidence that increasing age is accompanied by functional changes in those higher centres concerned with visual processing.

Performance on an embedded figures test (in which the subject is required to locate a simple geometric figure hidden within a more complex design) has been shown to be age-dependent (Lee and Pollack, 1978); older subjects required more time and had a higher failure rate than did younger subjects. Danziger and Salthouse (1978) presented subjects of various ages with incomplete figures (partially masked by an overlay of vertical and horizontal stripes) and asked them to identify the figure depicted - young subjects (mean age 19.3 years) performed significantly better on this unpaced task than did old subjects (mean age 70.3 years). In an earlier study, Verville and Cameron (1946) had shown that younger subjects responded quicker than older subjects when presented with incomplete figures for identification.

Backward masking studies have sought to separate peripheral from central factors. Identification of a briefly-presented target stimulus is detrimentally affected by the subsequent presentation of a masking pattern. The time interval between the onset of target presentation and that of mask presentation is known as *stimulus onset asynchrony* - as this critical interval increases, the masking effect of the second pattern becomes reduced until no longer effective. A homogeneous uncontoured masking stimulus is only effective when presented to the same eye as the target stimulus and hence is presumed to act at a 'peripheral' level, prior to the point at which convergence of binocular input occurs. A structured contoured pattern acts as a mask even when presented dichoptically and hence is regarded as acting 'centrally', at or beyond the point of binocular interaction (Turvey, 1973).

Several studies have used this basic paradigm to investigate the effects of ageing. Older subjects have been shown to have both peripheral deficits (Walsh, Till and Williams, 1978; Schlotterer et al, 1983) and central deficits (Walsh, 1976; Schlotterer et al, 1983), generally requiring longer inter-stimulus intervals to escape the effects of masking.

Weale (1975), having rejected optical factors as contributing in any significant way to the functional decline, postulated that the deterioration was instead due to random neuronal loss throughout the central nervous system. Assuming that the visual information passes through a series of stages, that cell death at one stage is independent of that at any other but that the amount of loss is similar at each stage, the resultant equation suggests that the decline in visual performance is due to changes occurring between stages 4 and 7 of the sequence. Although the anatomical location corresponding to each number remains unspecified, Weale speculates as to the likelihood that the level at which the change occurs might lie close to the decision-making centres.

This attempt to locate the site of the age-related changes assumes that cell death is occurring randomly throughout the central nervous system. This assumption may be questioned by Brody's (1955) findings that different brain areas are differentially affected by cell loss. In addition, since the relationship between structure (whether fine or gross) and function is still unknown there is the possibility that not only is cell death differential and non-random throughout the information processing sequence but that the loss at different levels (even if quantitatively identical) might have qualitatively different effects. The brain's well-known capacity for redundancy need not extend equally throughout its entire structure.

It is apparent that of the four levels of visual processing discussed here (all of which could easily be further sub-divided) only the first stage, the optical system, can at present be discounted from contributing in any significant way to the age-related deterioration in contrast sensitivity. Structural changes occur throughout the visual system and it seems more than likely that these alterations are related in some way to the observed and quantified functional deficits.

The reduction in contrast sensitivity with age may be due to differences in the way in which the ageing nervous system processes the visual information. Or it may be that the elevated thresholds are a result of age-related changes in decision-making.

In the present study, two methodological approaches - psychophysics and electrophysiology - have been used in an attempt to investigate these by no means mutually exclusive possibilities.

The work falls into two sections: in part 1, psychophysical techniques are employed in order to try to determine the contribution to the age-related decline made by changes in the decision-making behaviour of elderly people; in part 2, which involves electrophysiological techniques, an attempt is made to specify the manner in which age affects the visually evoked response elicited by presentation of a patterned stimulus (vertical sinusoidal grating pattern) of fixed physical contrast. There is also an attempt to interpret the electrophysiological changes in subjects of different ages by 'normalizing' stimulus contrast with reference to each individual's threshold.

INTRODUCTION: Psychophysics and decision-making

The psychophysicist is faced with a methodological problem rarely encountered in other areas of experimental investigation. In any psychophysical study the results obtained are wholly dependent on the responding of the subject - a 'black box' of motivations, impulses and drives all of which, though perhaps not bearing directly on the topic of experimentation, can indirectly affect its outcome. This problem is one which, at its most basic, would involve lack of cooperation; but the difficulties need not be as overt as, for example, the non-compliance of the recalcitrant pigeons and temperamental monkeys of comparative psychology or the irritable infants of developmental psychology. When the subject in question is an adult human then the problems attain a different order of complexity. The experimental subject brings to the laboratory a lifetime of accumulated knowledge and preconceptions which, in any number of ways, might influence the manner in which he or she approaches the experiment. Since the only information available to the experimenter is that which is provided by the subject one would obviously hope that he or she is participating in good faith and performing to the best of his or her abilities. In most cases, this situation will be the one usually encountered. However, the problem may be more insidious since there need be no conscious attempt on the part of the subject to provide misleading information, i.e. that which is not a precise description or account of their sensory experiences. Unconscious biases might exert an influence on the subject's responses. It is probably true to say that in any type of situation which involves the monitoring and measurement of some aspect of an individual's behaviour, the subject will generally try to perform in such a way as to present him or herself in the best possible light. What exactly this amounts to will, of course, depend on the individual in question. In striving for the optimal performance, different subjects might perceive their goal in different ways and might adjust their response behaviour in order to better achieve that goal. For instance, in a threshold-determining task, one subject might feel that the optimal strategy to adopt would be one in which they would respond in the affirmative only if they were absolutely certain that the stimulus was present. Another subject might feel that the best approach would be to report the presence of the stimulus on the basis of only the slightest evidence. Obviously, one would find that, all else being equal, the first subject would have a threshold which would appear elevated with respect to that of the second. In any case, it is clear that what was hoped to be a pure measure of sensitivity has become contaminated by factors other than those under investigation. A difficulty, then, with any attempt to establish sensory thresholds is how to evaluate the subject's response (i.e. "I can see / hear / feel it"). In situations where a person is asked to decide whether or not a signal is present it is usually impossible for the experimenter to distinguish between differences in the subject's detection threshold (i.e. whether or not they actually see it) and differences in response threshold (i.e. whether or not they *report* seeing it).

It is possible to partly circumvent the problem of inappropriate responding (e.g. false affirmatives) by the insertion into the protocol of *catch trials*, i.e. trials when no stimulus is presented. If the amount of false affirmatives is inordinately high then this might render suspect the subject's responding and the results could be either discarded or modified to take account of guessing behaviour. However, guesswork or lack of cooperation need not be the only reasons why false alarms might be made. Those instances where a subject responds 'Yes' to the absence of a stimulus are just as likely to be due to a genuine misinterpretation of his or her sensory experiences. The fact that such false affirmatives are made and the extent to which they are made provides interesting and useful information about the manner in which the subject evaluates and chooses to act upon the sensory information which he or she receives.

SIGNAL DETECTION THEORY

One method by which to systematically utilise the false alarm rate in order to disentangle the effects of an observer's perceptual sensitivity from his or her decision-making processes is to employ the theory of signal detection (SDT) in the analysis of the situation. SDT arose from work in the fields of statistical decision theory and electrical engineering. Its relevance and application to psychophysics was first suggested by Tanner and Swets (1954). Its chief innovation involved dispensing with the concept of an all-or-none threshold, replacing it with the notion that the sensitivity of the observer can be represented by a continuum. Prior to the development of SDT, the main school of thought was one which favoured the existence of a threshold to consciousness, conceptually identical to the threshold of firing by a nerve cell. Below a certain level or intensity of input, the centre in question (whether neurone or consciousness) remains unaffected by, or oblivious to, its external world. When a critical value of input intensity is reached, it produces an unambiguous effect on its target (action potential generation in the case of the nerve cell, detection of a signal in the case of consciousness). In SDT, on the other hand, all sensory input is considered to reach the decision-making centres, unimpeded by any peripheral barriers or thresholds. Although in a psychophysical detection task the observer's response behaviour may suggest the operation of a sensory threshold, it is in fact the adoption of a response criterion which leads to any particular stimulus being classified as 'present' or 'absent'.

Underlying signal detection theory are a number of assumptions. The first and most fundamental of these is that all sensory systems (regardless of modality) are marked by the presence of random noise: an inbuilt stochastic activity unrelated to (or at least uncorrelated with) the processing of the sensory information. The second assumption is that the distribution of this noise is Gaussian; the random (in the sense of 'non-specific') activity being described statistically by a normal curve. Following from this, it is assumed that the sensation (or more precisely, the neural activity correlated with the sensation) elicited by the presentation of a stimulus will be superimposed upon this background of noise; hence the sensation distribution will itself be Gaussian (Swets, Tanner & Birdsall, 1961).

The first and main assumption would appear to be a valid one since much evidence has been accumulated to suggest that sensory systems are indeed characterized by spontaneous activity therein. From a purely phenomenological viewpoint it is apparent that this is the case; for example, as regards the visual system, even in a darkened room with the eyes closed one still experiences the visual sensation known, depending on nationality or physiological partisanship, as cortical grey, dark light, *Eigenlicht* (Helmholtz, 1911), *Eigengrau* (Hering, 1878), or *Augenschwarz* (Fechner, 1860).

Experimental evidence in this area encompasses both psychophysical and electrophysiological research. Boring (1929) claimed that Gustav Fechner was the first investigator to report temporal variation in measures of sensory discrimination (although Fechner ascribed it to experimental error in measurement rather than variability in sensation). Urbantschitsch (1875) also reported that subjective estimation of stimulus magnitude fluctuated in time even though the stimulus was itself held constant (in this case, the ticking of a watch held a fixed distance from the ear, the subject reporting that the sound tended to fade and return. Several subjects confronted simultaneously with the same stimulus situation reported the same experience but their reports did not coincide in time, indicating that the effect was subjective and not due to physical changes in the external conditions). Guilford (1927) presents an early review of work in this field, research involving a number of modalities including vision.

Electrophysiological recording techniques have also served to indicate that the nervous system is spontaneously active. Granit (1955) reviewed a number of studies which have measured non-specific background activity in different modalities e.g. mechanoreceptors, stretch receptors, chemoreceptors etc. In the visual system, noise can arise due to random neural activity (Granit, 1955) or else - the latter perhaps being partly a consequence of - spontaneous degradation of photoreceptor molecules (Cane and Gregory, 1957).

As to the postulate that the activity is normally distributed: Barlow and Levick (1969) recorded retinal ganglion cell activity in the cat and found that, for the critical time period after stimulation within which a response appeared, the spontaneous activity (i.e. that which was recorded in the absence of a stimulus) was best fitted by a Gaussian curve. Kuffler, Fitzhugh and Barlow (1957) measured the maintained activity in the ganglion cells of the cat retina both in light and in darkness and found that it best fitted a hyperbolic normal distribution. Levine and Shefner (1977) found that around 50% of the goldfish retinal ganglion cell activity which they recorded could similarly be best fitted by a hyperbolic normal distribution (the remaining 50% had predominantly bi-modal distributions). In any case, statistical theory (central limit theorem) indicates that, in any system made up of the sum of a large number of independent and random variables with the same distribution (in this instance, the activity of single neurones) the sum tends towards a Gaussian distribution irrespective of the distribution of the random elements (Green and Swets, 1966).

The third proposition is that the sensation induced by a low intensity stimulus can only be separated from noise-induced effects on the basis of probability. This can be stated another way: the limiting factor in sensitivity is determined by the amount of noise present in the system. In the case of the visual pathway, even if it is presumed to operate as an ideal information processing system, its sensitivity will still be limited by the fluctuations in quanta absorbed by the retina (Barlow, 1962), fluctuations which are due to the probabilistic nature of photon emission. The uncertainty in the system will be further exacerbated by the retinal noise (and also by noise in subsequent parts of the pathway). Barlow (1957) has shown that the relationship between background light and threshold for a small incremental stimulus is one which agrees with the prediction that decisions made at near-threshold values of stimulus intensity are ones which can be considered as signal / noise discriminations.

The detection theory model can be represented diagrammatically by probability distributions as shown in Fig. 1.

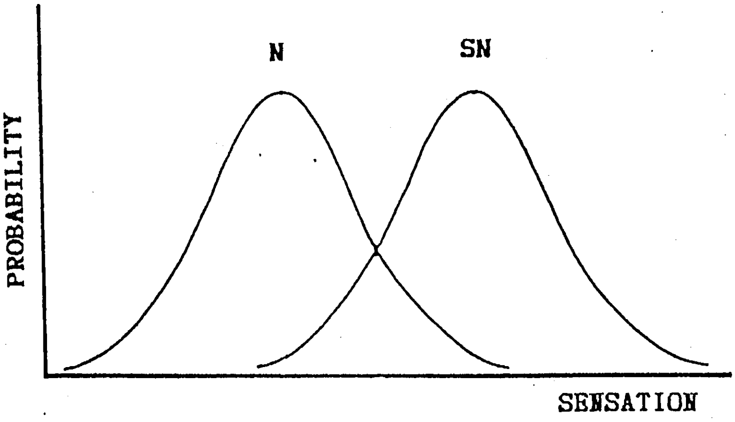
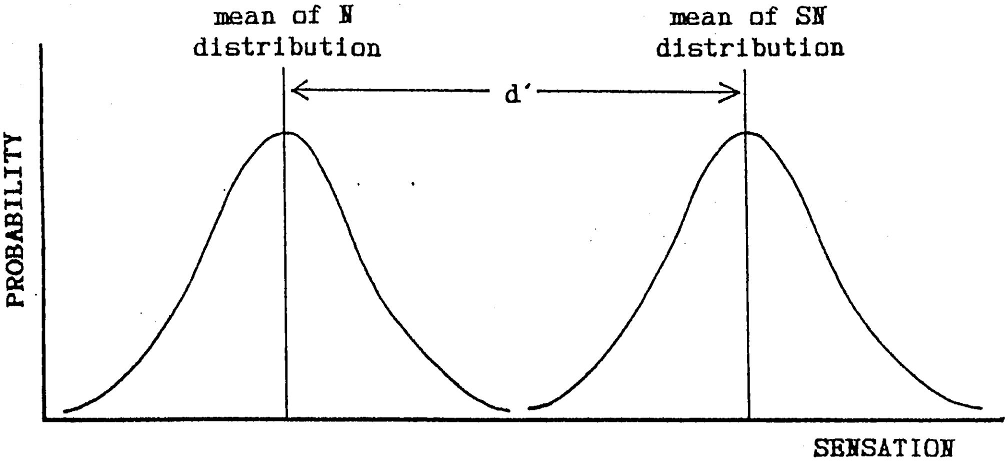


Fig. 1. Schematic representation of noise [N] and signal + noise [SN] distributions (see text for details).

In this schema the abscissa is the continuum of sensation; moving along this axis towards the right corresponds to an increase in the intensity of subjective sensation. The y-ordinate can be regarded as representing the likelihood of occurrence of any particular level of sensation. The distribution on the left is that associated with 'noise' [N], while that on the right is that of 'signal + noise' [SN]. The standard deviations of the [N] and [SN] distributions are assumed to be equal.

When a high intensity stimulus is presented then the sensation elicited will be so strong that the observer should have no difficulty in differentiating it from the noisy background. In terms of the model under discussion, the 'noise' and the 'signal + noise' distribution are separated to such an extent that no overlap (no area of ambiguity) occurs (Fig 2).



Fig, 2, d′ represents a measure of the observer's sensitivity (see text),

The difference between the means of the two distributions, which represents the ability of the subject to discriminate stimulus-induced sensation from noise-induced sensation, can be regarded as a measure of the subject's sensitivity. It is expressed in units of the common standard deviation and is designated, in the terminology of SDT, by the symbol *d′*.

In the situation opposite to that described above, when an observer is asked to detect the presence of a *low* intensity stimulus, then it will be more difficult to differentiate signal from noise (the means of the two distributions being closer together) and sensitivity will accordingly be reduced (Fig 3).

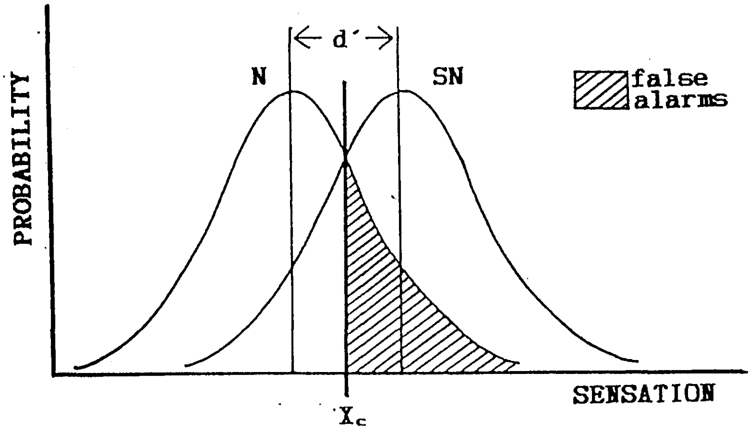


Fig. 3. X_c represents the observer's cut-off point or criterion (see text)

In such instances, occasions will arise when the available information will be ambiguous, i.e. there will be no way to be certain whether the sensation elicited is due to the stimulus or due to the noise (since the 'noise' distribution and the 'signal + noise' distribution will overlap). Sometimes the sensation will be due to the presence of the stimulus while other times the sensation will be due to noise alone (Fig. 3). SDT assumes that, faced with such a situation, the observer bases his or her decision on statistical factors. He or she must set a cut-off point (X_c) whereby any sensation above a certain level will be regarded as being produced by the stimulus and any sensation below this level will be regarded as being due to noise. Operating within this zone of ambiguity (where signal and noise can be differentiated only on the basis of probability) it is apparent that the possibility exists that a sensation elicited by noise alone might be regarded incorrectly by the subject as being due to the stimulus; hence there is the likelihood that false alarms might occur. It can be seen that, for any point on the sensation axis within the area of overlap, there exists a unique description of the subject's criterion (designated by the symbol β) based on the ratio of the heights of the two frequency distributions at the cut-off point X_c. The setting of this criterion provides an indication of the decisional strategy employed by the subject.

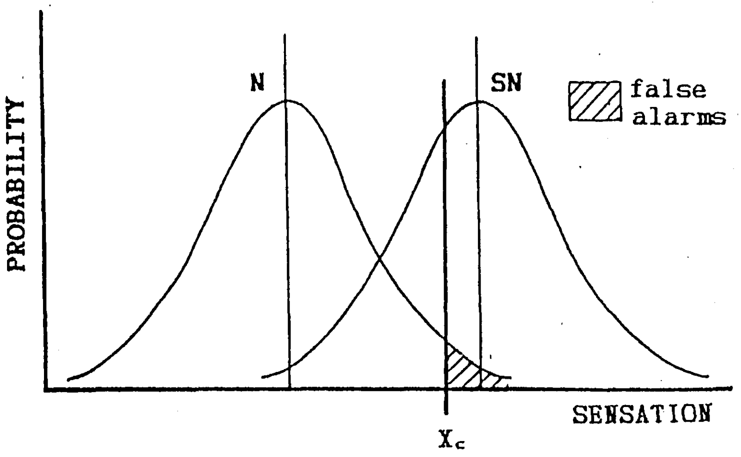


Fig. 4. Schematic representation of observer with 'strict' criterion.

For example, in Fig. 4 the subject is fairly conservative in his or her response behaviour; although a small proportion of false alarms will be made, this is counterbalanced by the fact that a reduced number of hits will be obtained. In Fig. 5 the subject is less cautious. Although obtaining a higher hit rate than the subject represented by Fig. 4 this would be at the expense of a much higher false alarm rate.

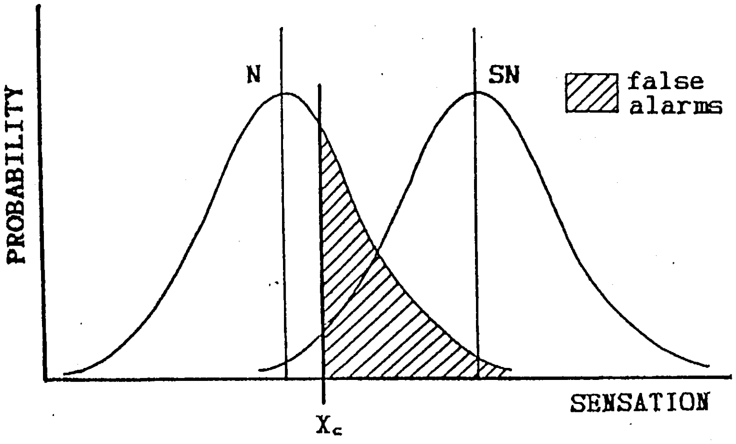


Fig. 5. Schematic representation of observer with 'lax' criterion.

In the experimental situation it is possible to manipulate the placement of the criterion by varying either the probability of stimulus presentation or the payoffs (rewards and demerits) for right and wrong decisions.

DECISION-MAKING AND AGEING

SDT allows a distinction to be drawn between a person's sensitivity (the ability to differentiate the signal from the neural noise on which it is superimposed) and the criterion he or she employs in deciding whether or not to report the sensation elicited by the signal (above the pre-set and individual criterion the subject should always report perceiving the signal; below the criterion the subject should always decide that the stimulus was <u>not</u> presented and that any subjective sensation was due merely to noise). A possible explanation, then, for the reduced contrast sensitivity with age is that, for whatever reason, the elderly observer is more conservative in his or her judgements than a younger person. In other words the old observer might require more evidence (e.g. greater contrast) before committing him or herself to a decision as to whether the stimulus is present.

There is experimental evidence to suggest that advancing years are indeed accompanied by an increasing decisional conservatism. When subjects of all ages were presented with an imaginary 'real-life' situation (e.g. choosing between a secure but poorly-paid job and an insecure but highly-paid job) and asked to decide what probability of success would be required before embarking on the more risky course of action, elderly subjects tended to be more cautious in their decisions than younger people (Wallach and Kogan, 1961). Similar findings were obtained by Botwinick (1966) who, in addition, used situations which had more relevance to older people (e.g. choosing between a secure life with the family or a less secure but more independent life-style).

In the field of perceptual psychology, attempts to determine the contribution of the subjective criterion to age-related changes in sensory performance have been few and far between and, moreover, have yielded conflicting results. Rees and Botwinick (1971) investigated how elderly subjects compared with younger subjects in detection of an auditory signal. They found that the sensitivity did not change with age whereas the criterion did. The older group was, in fact, more 'stringent' than the young group, i.e. they would be more reluctant to acknowledge the presence of a signal even although it apparently produced an event in consciousness similar to that experienced by younger people (18-21 yrs as compared with 65-77 yrs).

Potash and Jones (1977) also used an auditory stimulus (a 6000Hz tone against a background of noise). Although, in absolute terms, older subjects (mean age 58 yrs) were less sensitive than young subjects (mean age 23 yrs), a comparison of criterion at the stimulus intensities which gave equivalent sensitivities (30dB in young and 50dB in old) showed that old subjects were more conservative than young.

A number of studies have used pain as the stimulus. Clark and Mehl (1971) applied radiant heat to the forearm of subjects ranging in age from 18 to 67 yrs. Older subjects (mean age of 43.8 yrs in males and 49.4 yrs in females) were found to adopt a more strict criterion than did young subjects (mean age of 23.9

yrs in males and 22.2 yrs in females). In other words, their categorization of stimulus intensity in terms of its noxious effects was biased towards reporting it as non-painful. Similar conclusions were drawn by Harkins and Chapman (1976) who used electrical stimulation of tooth pulp as the stimulus. Old male subjects (mean age 71 yrs) were less willing than their young counterparts (mean age 24 yrs) to classify low intensity shocks as painful (although the older subjects were more willing than the young subjects to report shocks of greater intensity as being painful). The same authors obtained similar results (a bias in old subjects against classifying mild shock as painful) when the study was replicated with only female subjects (Harkins and Chapman, 1977).

A forced choice procedure was employed by Vaegan and Halliday (1982) in the determination of contrast sensitivities in subjects of different ages. This method required the subject to decide the orientation of low contrast printed grating patterns. With such a technique, criterion differences should have less of an influence on threshold measurements. In fact, the age-related decline obtained using an ascending method (with both Arden gratings and oscilloscope-generated gratings) was no longer present for spatial frequencies at or below 3.2 c/deg.

However, in other areas of age-related perceptual decline, the use of a forced choice procedure has been less successful in eliminating the differences observed in older people. For example, Danziger and Salthouse (1978) found no evidence to suggest that a higher criterion was responsible for the poorer performance of older adults (mean age 70.3 yrs) in identification of incomplete figures. Similarly, Watson, Turpenoff, Kelly and Botwinick (1979) concluded that there was no difference in criterion between young and old subjects as assessed by performance on a weight discrimination task. This study involved only female subjects but Watson et al suggested that the apparent conflict with the earlier results of Rees and Botwinick (1971) was due, not to sex differences, but to the fact that the increased conservatism in old might only become apparent when the task or modality under investigation is one in which older subjects are already somewhat handicapped with respect to young i.e. genuine sensitivity changes are magnified by the additional complication of criterion differences. In other words, the older subject is reluctant to make a response to a signal which, relative to young, has been degraded in some way by purely sensory changes.

In the area of visual perception, Sokol, Domar and Moskowitz (1980), measuring contrast sensitivity in subjects aged from 6 to 82 years using the Arden gratings, reported that above 50 years of age there was an increase in the false positive rate (analogous to false alarms). This might be suggestive of a more lax criterion in older subjects. Using detection theory, Hutman and Sekuler (1980) compared younger to older subjects in their detection of the presence of a grating pattern (1 c/deg). The contrast used was 1.25x the appropriate threshold value, the stimulus duration was 0.5 secs, and the probability of presentation was 50% over 100 trials. The subjects were asked to report their opinions on whether or not the signal had been presented, in the form of a scale (1 - 6; 1 = 'definitely present', 6 = 'definitely absent'). The results revealed no differences in the two groups either in terms of sensitivity or in response bias (differences in the latter would indicate a tendency towards a particular response, e.g. denying that the grating was present). However, one positive finding was that the older subjects (mean age 73 years) were less likely to use the extremes of the rating scale, indicating what might be looked upon as an increased tendency towards cautiousness in the older observers. While the similarity in sensitivity between the two age groups (young group had mean age 18.4 years) is not surprising given that perceived contrast had been made psychophysically equivalent, the more cautious response behaviour of the elderly subjects is more interesting and seems to indicate an effect which conventional psychophysical threshold-determining techniques would probably fail to uncover.

Given the limited use of the technique in the area of age-related visual decline (and given the ambiguous and inconclusive results - witness the appparently conflicting results of Hutman and Sekuler (1980) and Vaegan and Halliday (1982)) - it was felt that a further application of signal detection theory across a wide age range might prove fruitful.

In the present study, it was decided that (for reasons to be discussed in the Methods section) a simple 'Yes-No' paradigm was more appropriate than a rating scale in a comparison across the ages tested. In addition, rather than the single contrast multiple used by Hutman and Sekuler (1980), (which yielded hit rates near to perfect detection and hence might have been comparing age groups on performances which were close to or at saturation) a range of contrasts were used, derived from the contrast threshold but chosen according to the individual needs and abilities of each subject.

Previous reports of this work appeared in Morrison and Reilly (1986a and b).

[illegible] of the [illegible] subjects, were [illegible] from the Institute of Psychology, University of Glasgow. The [illegible] the older subjects were from senior citizen's [illegible] organisations from within the local area. These individuals were in good health and were alert in mind. [illegible] great willingness to assist in the experiments and an [illegible] to perform to the best of their ability. The age [illegible] the subjects was as follows (the number in each decade [illegible] in parentheses): [illegible] ([illegible] male, [illegible] female), 30s (1 male, [illegible] 40s (nil), 50s (2 male, [illegible] female), 60s (4 male, 3 female), [illegible] male, 5 female), 80s (1 male, 2 females) and 90s (1 male) an intraocular lens implant in one eye following extraction. Vision in the unoperated eye was normal fo age. The tests took place in a darkened room and generall [illegible]

METHODS

SUBJECTS

Experiments were carried out on 46 unpaid volunteers ranging in age from 21 to 92 years. Almost all of the young subjects, and some of the older subjects, were recruited from within the Institute of Physiology, University of Glasgow. The majority of the older subjects were from senior citizen's community organizations from within the local area. These latter individuals were in good health and were alert in mind, showing great willingness to assist in the experiments and an eagerness to perform to the best of their ability. The age distribution of the subjects was as follows (the number in each decade indicated in parentheses): 20s (9 male, 7 female), 30s (1 male, 2 female), 40s (nil), 50s (2 male, 2 female), 60s (4 male, 3 female), 70s (7 male, 5 female), 80s (1 male, 2 females) and 90s (1 male). Visual acuity was tested using a back-illuminated Snellen chart from a viewing distance of 5 metres. All subjects had a Snellen acuity which was normal for their age and wore their best correction if necessary. Subjects were also examined for astigmatism and, if required, were corrected with cyrindrical lenses. Viewing was binocular. Two of the elderly subjects, ages 76 and 81 yrs, had an intraocular lens implant in one eye following cataract extraction. Vision in the unoperated eye was normal for their age. The tests took place in a darkened room and generally lasted two hours with additional breaks.

STIMULUS DISPLAY

The form of stimulus used was a vertical sinusoidal grating pattern. A raster was generated on a Tektronix 606B monitor (P31 phosphor, peak wave-length 520nm) by a 770kHz triangular wave fed into the vertical amplifier. This was modulated by a sine wave produced by a Feedback oscillator (SS06603) and fed into the Z-modulation. The time-base was driven by the X-output of a Tektronix 5103 oscilloscope running at 0.2ms/div which also monitored the frequency and amplitude of the sine wave grating pattern (Fig. 6).

The contrast of the pattern, described by the formula

$$(L^{MAX}-L^{MIN}) \ / \ (L^{MAX}+L^{MIN}),$$

was determined using the psychophysical contrast matching technique proposed by Campbell and Green (1965). A small window was placed over the screen so that only one cycle of a square wave grating pattern was visible. The brighter half of the cycle was then covered with a neutral density filter of known value and the modulating voltage adjusted until an observer matched the filter with the darker half of the cycle. The voltage could then be calibrated in terms of contrast units. Three subjects performed the matching over a range of neutral density filters. The

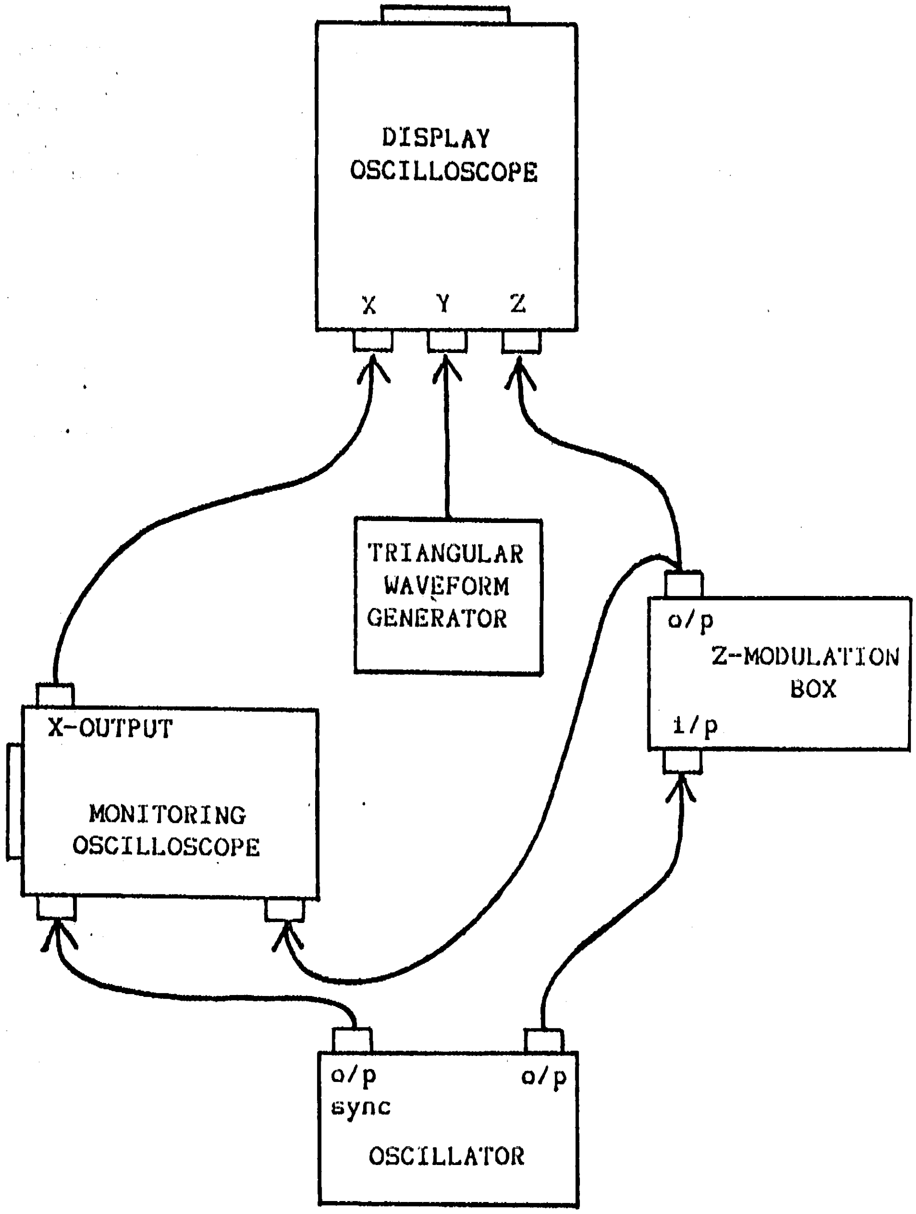


FIGURE 6. Block diagram illustrating method of generating sinusoidal grating pattern.

contrast of the grating pattern was linearly related to the Z-modulation voltage (0.253 contrast units / Volts peak-to-peak up to 3V, maximum contrast of 0.85 at 5V; see Figure 1 in Appendix). Contrast was adjusted using a ten-turn potentiometer control unit and could be varied without altering the mean luminance across the display screen.

Two spatial frequencies were used: 3 c/deg (at the peak of the contrast sensitivity function) and 15 c/deg (a moderately high spatial frequency). The former was viewed from a distance of 1.43m; the latter from 2.86m. At the far distance, the transfer characteristics of the cathode ray tube still give unattenuated contrast for the higher spatial frequency. The spot size was comparatively small (0.08mm in diameter) ensuring good resolution and allowing a greater number of lines across the screen. The near distance was used in order to maintain a reasonable number of cycles on the screen since sensitivity is compromised if the display contains only a small number of cycles (Hoekstra et al, 1974). It has been shown that the results of the contrast sensitivity determinations for different viewing distances can be combined in a single contrast sensitivity function (Campbell and Robson, 1968). The display was viewed through a window in green cardboard and subtended 4 deg arc at the near distance and 2 deg arc at the far distance. The screen luminance (measured using a Pentax Spotmeter) was 3.0 foot-Lambert (10.2 cd/m^2) while the background luminance, provided by the indirect lighting from two spot lamps, was 0.5 metre-candela (measured with a Lightmaster Photometer).

CONTRAST SENSITIVITY

Prior to the signal detection experiment, contrast thresholds were determined for the two spatial frequencies used. This was done using an ascending method in which the subject, using the aforementioned control unit, was asked to gradually increase the contrast of the grating pattern from a uniform screen until the point where the pattern was just visible and no more. Further fine contrast adjustments were allowed. The experimenter was able to independently adjust the sensitivity of the control unit by varying the output of the oscillator (which determined the amplitude of the sine wave). This was done in order that the subject would have a reasonable number of turns of the potentiometer before threshold was reached and also so that he or she could not use the number of turns as a possible cue to estimating threshold. Ten such determinations were made and the average taken to obtain the contrast threshold, the reciprocal of which gave contrast sensitivity.

SIGNAL DETECTION

The stimuli used in the detection experiment were grating patterns of contrasts which were multiples of the above threshold, thus ensuring that stimuli were psychophysically comparable from subject to subject. Hutman and Sekuler (1980) used as the stimulus in their detection experiment a grating pattern of contrast 1.25x the threshold value. Experiments carried out as preliminaries to the present study indicated that using a single contrast multiplier would be unsatisfactory. A pattern of 1.25x threshold was, for some subjects, easy to detect and hence yielded a 100% hit rate (rendering calculation of sensitivity and criterion impossible); for other subjects, the same contrast (suprathreshold using the ascending method) appeared to be subthreshold in the context of the detection paradigm (i.e. gave a 0% hit rate, sensitivity and criterion again not being calculable). It was decided that it would be more appropriate to use several contrast multiples, the exact range of which would be tailored to suit the response behaviour of each subject. The decision as to the actual values of contrast multiple which were used for each subject was taken by the experimenter during the session. If a particular contrast yielded a high detection rate then the next run would use a stimulus of a lower contrast; by this method the extremes of the subject's detection performance were determined and intermediate values of responding subsequently obtained. The contrasts used generally lay within the range 0.8x to 2.0x threshold. However, in the case of some observers it was necessary to use contrasts which were higher or lower than this in order to ensure a reasonable level of successful detection. Several contrast levels (usually 6) were used at each spatial frequency. Since each trial required the subject to maintain a high level of concentration, a few minutes break was allowed between trials in order to minimize fatigue and possible lapses of attention. In addition, there was a longer break of about 15 minutes between the 3 c/deg and 15 c/deg block of runs.

During the familiarization procedure the grating pattern used as a demonstration was of a very high contrast in order that the relationship between the pattern and the tone might be made obvious. Subjects were made aware of the fact that the pattern used in the experiment proper would be of a much lower contrast. It was emphasised that the pattern would be very faint and, while there would always be the same number of presentations in each run, in those instances where the contrast was low the subject might not necessarily see the pattern every time it was presented. An attempt was made to keep both the wording and the tone of the instructions as neutral and as consistent as possible. Although the subjects were told that the purpose of the experiment was to assess their ability to detect faint patterns, no mention was made of criterion or response biases.

Prior to the experiment a short practice session was allowed using as stimulus a high contrast pattern. In the experiment proper, contrasts were presented in a pseudo-random order although the first run used a contrast which was markedly suprathreshold (e.g. 160% of contrast threshold) in order to allow the subject to become more familiar with the procedure and to minimize frustration and uncertainty effects (Davis and Graham, 1981).

Although the use of a rating scale procedure is standard practice in many signal detection experiments, it was decided that a simple 'Yes - No' task would be sufficient for the purposes of this experiment and that the extra information which a rating scale format could provide was not of sufficient value, in the context of the present study, to make worthwhile burdening the subject with the task of allocating their responses to arbitrary (and possibly confusing) confidence categories. It was felt that a straightforward comparison between young and old subjects on measures of sensitivity and criterion might have been compromised by a protocol which relied too heavily on the subjects' ability to understand and retain the rating scale categories with which they were provided; problems must surely arise if the possible responses become so many and so abstruse as to render difficult a straight-forward categorization. For instance, Hutman and Sekuler (1980) instructed their subjects to categorize their response according to a scale indicating their level of confidence. It is difficult to see which kind of perceptual experience would be required in order to elicit the response, 'There possibly were *not* bars on the screen', one of the six categories in Hutman and Sekuler's scale. This problem, if itself age-related, might confound a comparison of young and old subjects.

In the present study, each trial was signalled by an auditory tone of 0.5 sec duration, triggered by a Devices Digitimer and presented every three seconds, 50 consecutive times (Fig. 7). On 25 of these presentations a low contrast grating pattern, similarly triggered, was displayed on the oscilloscope screen to coincide with the tone. Presentation was controlled by the experimenter according to random tables. Hence, each time the tone was heard, there was a 50% chance of the visual stimulus being present. The subject had to decide whether he or she had

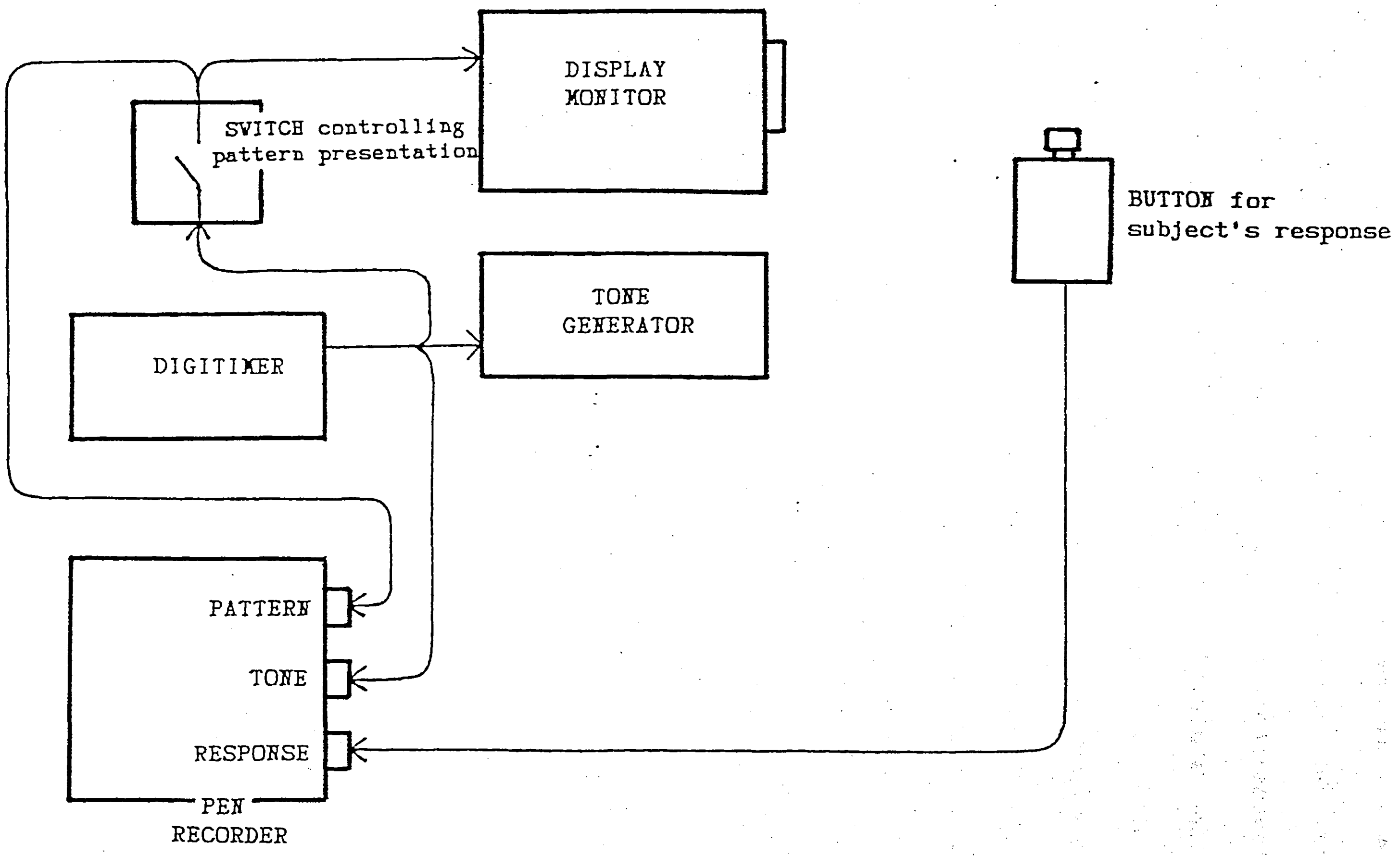


FIGURE 7. Schematic representation of signal detection experimental set-up.

seen the pattern and, if their decision was in the affirmative, had to indicate so by pressing a button. The response was recorded on a Devices chart recorder which also recorded tone and pattern presentation. The protocol therefore allowed four possible outcomes on each trial: the subject could press the button when the pattern was present (Hit); the subject could press the button when the pattern was *not* present (False alarm); the subject could fail to respond when the pattern was present (Miss); the subject could decide not to respond when the pattern was not present (Correct rejection) (Fig. 8).

		RESPONSE	
		yes	no
SIGNAL	present	HIT	MISS
	absent	FALSE ALARM	CORRECT REJECTION

FIGURE 8. Matrix showing the four possible outcomes of the detection protocol.

CALCULATION OF SENSITIVITY AND CRITERION

From the experimental records, the hit rate (p[HIT] - the number of correct detections expressed as a fraction of 25 target presentations) and false alarm rate (p[FA] - the number of incorrect positive identifications expressed as a fraction of 25 trials when no target is presented) could be obtained.

The observer's hit rate (p[HIT]) is therefore the area under the SN distribution to the right of X_c while the false alarm rate (p[FA]) will be the area under the N distribution to the right of X_c (X_c being the cut-off point which the individual uses as the dividing line between stimulus and noise) (see Fig. 3 in SDT Introduction).

A[HIT], defined as the area under the SN distribution between X_c and the mean, can then be determined (p[HIT] - 0.5); likewise for the area under the N distribution between the mean and X_c (A[FA] = 0.5 - p[FA]). The distance between the means of the two distributions is a measure of the signal and noise discriminability (or subject sensitivity). A[HIT] and A[FA] are then converted into units of standard deviation (Z scores) and added together to give d′.

$$d' = Z[HIT] + Z[FA]$$

This formula (Coren, Porac and Ward, 1979) applies only if p[HIT] is greater than 0.5 and p[FA] is less than 0.5. In other circumstances appropriately modified versions of the formula were used.

When p[HIT] > 0.5 and p[FA] $\geqslant 0.5$, then the formula used was

$$d' = Z[HIT] - Z[FA];$$

when p[HIT] $\leqslant 0.5$ and p[FA] < 0.5, the formula used was

$$d' = Z[FA] - Z[HIT];$$

when p[HIT] < 0.5 and p[FA] > 0.5, the formula used was

$$d' = -(Z[HIT] + Z[FA]).$$

The more sensitive the subject then the higher the value of d′. Using the present protocol it was possible to obtain values extending from approximately $d' = 3.5$, maximum sensitivity, where the subject makes 24 / 25 correct detections (p[HIT] of 96%) with only 1 / 25 false alarms (p[FA] of 4%), down to a theoretical minimum d′ score of approximately -3.5. This latter value would only occur if the observer had a 4% hit rate and a 96% false alarm rate, a highly unlikely situation which would suggest non-comprehension or non-cooperation rather than reduced sensitivity. A more likely minimum score of d′ would tend to lie at 0, indicating an equal number of hits and false alarms (i.e. chance responding), although slightly negative d' scores can of course occur if the subject *is* responding according to chance and if the false alarms should even only marginally outnumber the hits.

Normal probability tables give values for the ordinates of each distribution at X_C and the ratio of these two (O[HIT] / O[FA]) provides an index of the subject's criterion (β) (Coren, Porac and Ward, 1979). The higher the value of β then the stricter, i.e. more conservative, the criterion adopted by the subject. A limitation with this procedure is that it is not possible to include in the calculation those trials which yielded a 0% false alarm rate or a 100% hit rate.

An alternative method which, in the present study, was used in conjunction with the above, is that proposed by Hodos (1970). It has the advantage that criterion values can be calculated even when hit rate is 100% and false alarm rate is 0%. In addition, unlike detection theory it makes no assumptions about the underlying distributions of signal and noise. In this model the criterion is known as *percentage bias* and can extend from -100% through 0 to +100%.

The subject's p[HIT] is plotted against p[FA] (Fig. 9).

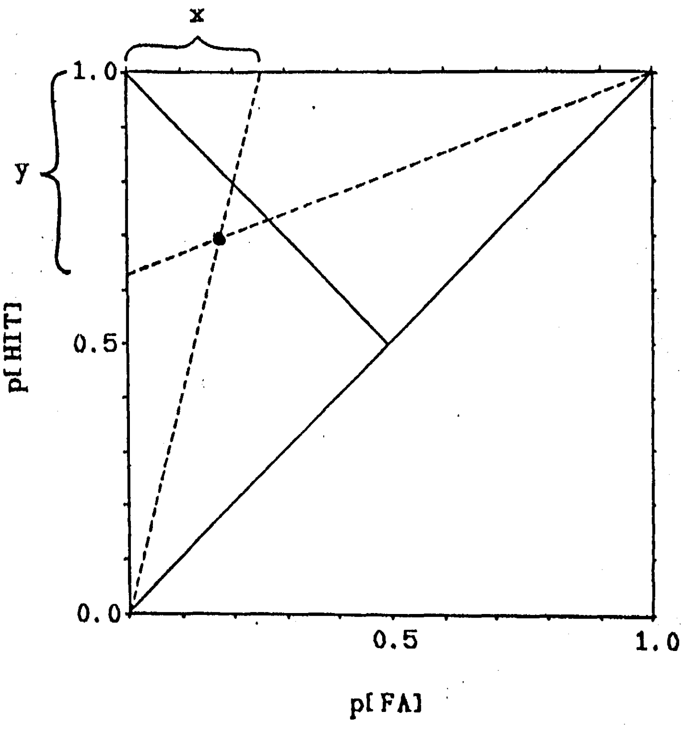


FIGURE 9, Graphical method of calculating percentage bias (after Hodos, 1970), If the point should fall on the y-axis then this is representative of a subject who would be biased towards not responding, i.e. in instances of ambiguity, when uncertain as to the origin of the subjective sensation, the subject would tend towards interpreting the perceptual experience as being due to noise and would hence classify it accordingly, responding in the negative. If the point should lie on the x-axis at the top of the square then this is indicative of a subject maximally biased towards responding in the affirmative i.e. classifying ambiguous percepts as being stimulus-induced. A point lying on the negative diagonal (sloping downwards from left to right) would represent the performance of a subject who, in situations of uncertainty, would be just as likely to respond in the affirmative as in the negative.

In this graphical method, bias is calculated by drawing a reference line from the origin through the plotted point until it intercepts the axis at the top of the square (see Fig. 9). A second line is drawn from the top right hand corner (1,1) through the point in question and intercepting with the y-axis. Two overlapping triangles are formed. The relative areas of these two triangles gives a measure of subject bias. As a simplification, the relationship can be expressed in terms of the dimensions of the triangle bases (x and y in Fig. 9). If the point should lie to the left of the negative diagonal (as shown in the figure) then the formula used is

$$\% \text{ BIAS} = [y-x\ /\ y].100$$

If the point plotted should fall to the right of the negative diagonal then the formula used instead is

$$\% \text{ BIAS} = [y-x\ /\ x].100$$

In practice, the graphical method was felt to be unnecessarily time consuming. It was decided that a very similar measure of bias could be obtained by using the same formulae but instead assuming that, when $p[\text{HIT}] = 1.0$ or $p[\text{FA}] = 0.0$:

$$y = 1.0 - p[\text{HIT}] \text{ and } x = p[\text{FA}].$$

Possible differences in reaction time between young and old were not considered to be important since they were unlikely to be of an order which could affect the outcome of the experiment. (Birren, Riegle & Morrison (1962) found an age-related increase of only 16 msec, a time well within the 'response window' of the present study).

A short series of preliminary tests sought to investigate the possibility of using reaction time as an index of subject confidence. Assuming that level of sensation and level of confidence are related (i.e. the subject should feel more confident about his or her response when the sensation elicited is intense), and given that reaction time is inversely related to stimulus intensity (Cattell, 1886), it follows that reaction time could be regarded as a measure of the subject's confidence in their response and would, in effect, provide similar information to that of a rating scale. Gish, Shulman, Sheehy & Leibowitz (1986) showed that reaction time decreased as detection rate increased (i.e. the more detectable a stimulus, the faster the subject responded to its presentation). Although this system might have provided the requisite information, in practice it would have been unrealistic to expect subjects to maintain concentration for the duration of time required to amass the necessary data. Since most observers tended to make few false alarms, a large number of trials would have to be run in order that a sufficient amount of false alarms (and their associated reaction times) might have been obtained. A further, more practical objection is that in order to resolve the relatively small differences in reaction time between young and old the chart recorder would have to be run at a fast speed and hence each experiment would require an inordinate amount of chart paper. Hence, the idea was not developed further.

It should be noted that a small number of subjects appeared to have difficulty in coping with the demands of the detection task. For example, in the case of one individual it became apparent after inspection of results on termination of the experiment (although was not immediately obvious during the experiment) that she had been pressing the button when the stimulus was not present (contrary to instructions). Although it might have been possible to salvage the experiment by 'reversing' the results (i.e. regarding her positive responses as 'misses' and her failure to respond as 'hits') it was felt that it was unacceptable to consider her performance as typical and hence the results were omitted from the analysis. A number of other results were also excluded, in these instances because the subject's responding appeared to bear no temporal relation to tone presentation i.e. button-pressing could occur (sometimes more than once) even in the breaks between tones. Of the total number of subjects who were tested (50), only four were rejected on these bases and were excluded from the statistical analysis.

In the case of one subject, who at the outset appeared to be unable to cope with the task, it was found that the reason for her poor performance (complete failure to respond) was not lack of understanding but lack of hearing. By repositioning the tone generator in closer proximity to the subject's ear the experiment was able to proceed as normal.

[illegible] the gro [illegible] latter group [illegible] group (n=16, mean age 77.2 years, range 72-92 years).

In general, most measured values showed a Gaussian dist and were analysed using a conventional t-test. Val percentage bias were, however, negatively skewed alternative, non-parametric statistical comparison was the Mann-Whitney test.

RESULTS

For the purposes of statistical analysis the subjects were divided into two groups: a 'Young' group (n=19, mean age 25.5 years, range 21-38 years) and an 'Old' group (n=27, mean age 70.8 years, range 55-92 years). To avoid the possibility that the younger members of the 'Old' group (i.e. those in their fifties and sixties) were biasing the performance of the group as a whole, and hence masking any possible significant differences between young and old, a second analysis was performed with the latter group restricted to those aged 70 or over, forming a 'Very Old' group (n=16, mean age 77.2 years, range 72-92 years).

In general, most measured values showed a Gaussian distribution and were analysed using a conventional *t*-test. Values of percentage bias were, however, negatively skewed and an alternative, non-parametric statistical comparison was applied, the Mann-Whitney test.

Visual acuity

Acuity was found to be within the normal range for the ages of the subjects (Weale, 1975). In the young group the mean acuity was 5/4; in the old group acuity was 5/6.6; in the very old group acuity was 5/8.

Contrast sensitivity

Using a conventional ascending method of threshold determination, contrast sensitivity at 3 c/deg was significantly lower in old and very old subjects compared with younger subjects ($p<0.001$ in both cases). In these and all subsequent instances, values of contrast sensitivity will be given in logarithmic units. In the young group the mean contrast sensitivity was 2.29 (standard error ±0.05); in the old group the mean contrast sensitivity was 2.06 ±0.04 while that of the very old group was 1.95 ±0.04 (Fig. 10). At 15 c/deg contrast sensitivity was again significantly lower in old and very old subjects ($p<0.001$). In the younger group the mean contrast sensitivity was 1.51 ±0.06; in the old group it was 0.95 ±0.08 while in the very old group it was 0.71 ±0.08 (Fig. 10).

Signal detection

The relationship between detection performance and stimulus contrast was of roughly the same form for each individual irrespective of age (Fig. 11). As contrast was increased, hit rate rose also, from low detection at low contrasts (low multiples of threshold) to 100% detection at higher contrasts.

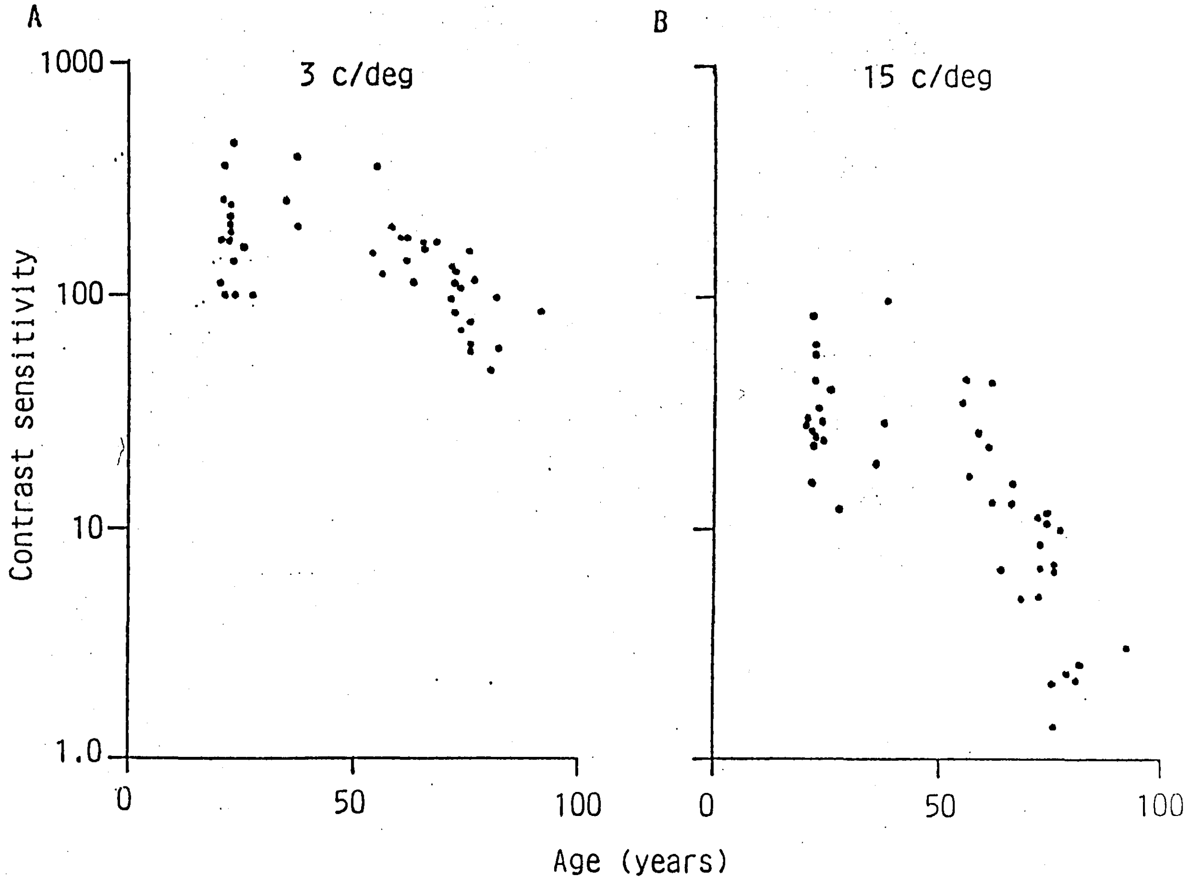


FIGURE 10. Contrast sensitivity (logarithmic units) determined by the ascending method for 3 c/deg (A) and 15 c/deg (B) at different ages.

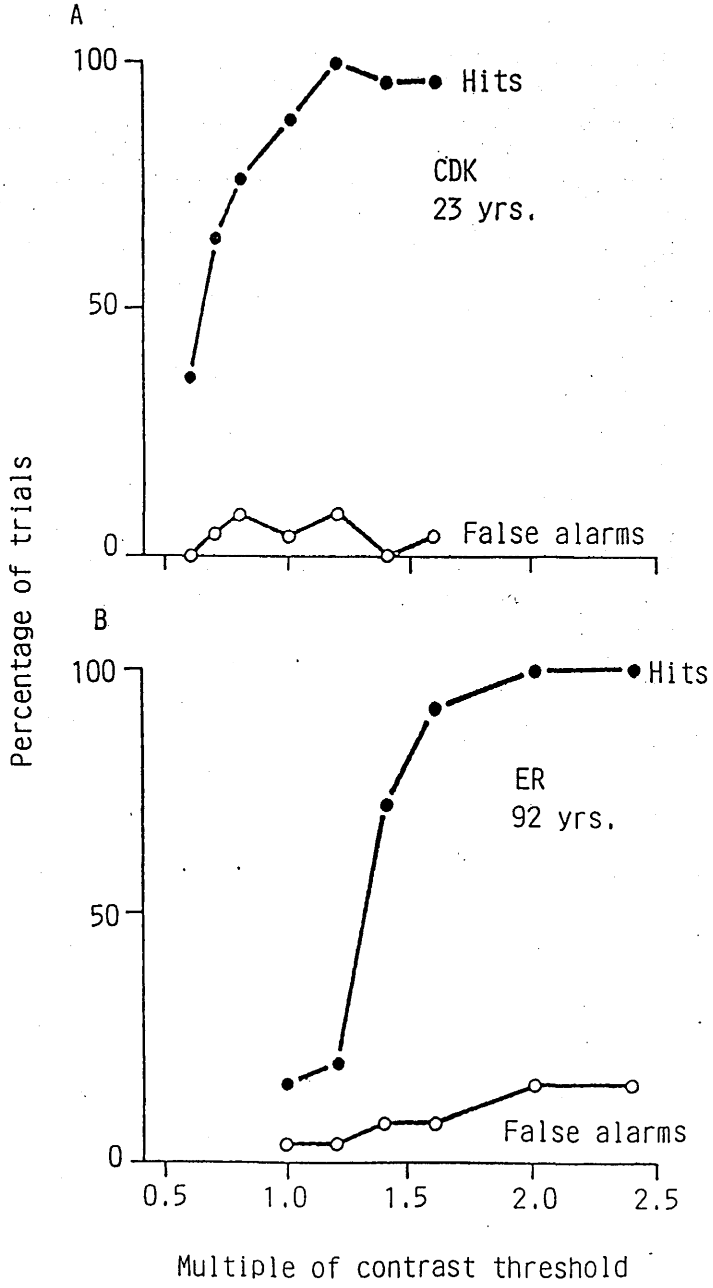


FIGURE 11. Hit rate and false alarm rate at increasing multiples of contrast threshold determined by the ascending method at 15 c/deg for a typical young subject (A) and a typical old subject (B). Contrast thresholds were 2.3% and 30.9% respectively.

False alarm rate, while displaying a certain amount of variation across the range of contrasts used, did not show any significant trend with increasing contrast. At highest contrasts, false alarms tended to fall to zero because the pattern was relatively easy to see and therefore the probability of making any incorrect detections were small. At the lowest contrasts which were used, false alarm rate could either fall to zero or increase slightly. In the former case this was because, in the situation where it was virtually impossible to see the pattern and hence extremely difficult to differentiate it from the noise trials, some subjects tended to reduce responding to a bare minimum. In the latter case it was because, with the stimulus difficult to detect, some subjects tended towards chance responding, hence increasing the false alarm rate until it was the same as the hit rate. There were no apparent age-related trends in the adoption of either strategy.

Verbal reports

In the breaks between trials and at the completion of the experiment subjects were encouraged to make any comment on the way in which they were approaching the task and the way in which they felt the experiment was progressing. It was apparent that most of the subjects generally considered a false alarm to be somehow more 'incorrect' than a miss. One subject stated that, of the two possibilities for inappropriate responding, they "...would rather miss it [than make a false alarm]" and that they were "... frightened to press in case it's not there...".

Another, that they "...wouldn't take a guess at it..."; another, that they "...didn't press unless I was really sure it was visible...".

At the lower contrasts it was clear that subjects were well aware of the ambiguous nature of their percepts; typical comments were that it was "...so easy to imagine lines...," that the subject was "...seeing mirages...," and that they sometimes had to make a "...value judgement..." based on the information available to them.

Although detection and contrast were similarly related in subjects of all ages it is apparent from the examples given in Figure 11 that the range of contrasts over which the full extent of detection performance occurred (i.e. lowest to highest hit rates) was different in young and old subjects. For instance, in Figure 11 the extremes of the young subject's detection performance occur at 0.6x and 1.2x contrast threshold whereas in the case of the old subject they lie at 1.0x and 2.0x contrast threshold i.e. shifted to higher multiples of the pre-determined threshold.

In the signal detection task, the contrast which yielded a 50% hit rate can be considered as an alternative measure of threshold. As can be seen from Figure 12 this contrast was actually a multiple of the pre-determined contrast threshold. At 3 c/deg the multiple in question was 1.46 ±0.13 in old people,

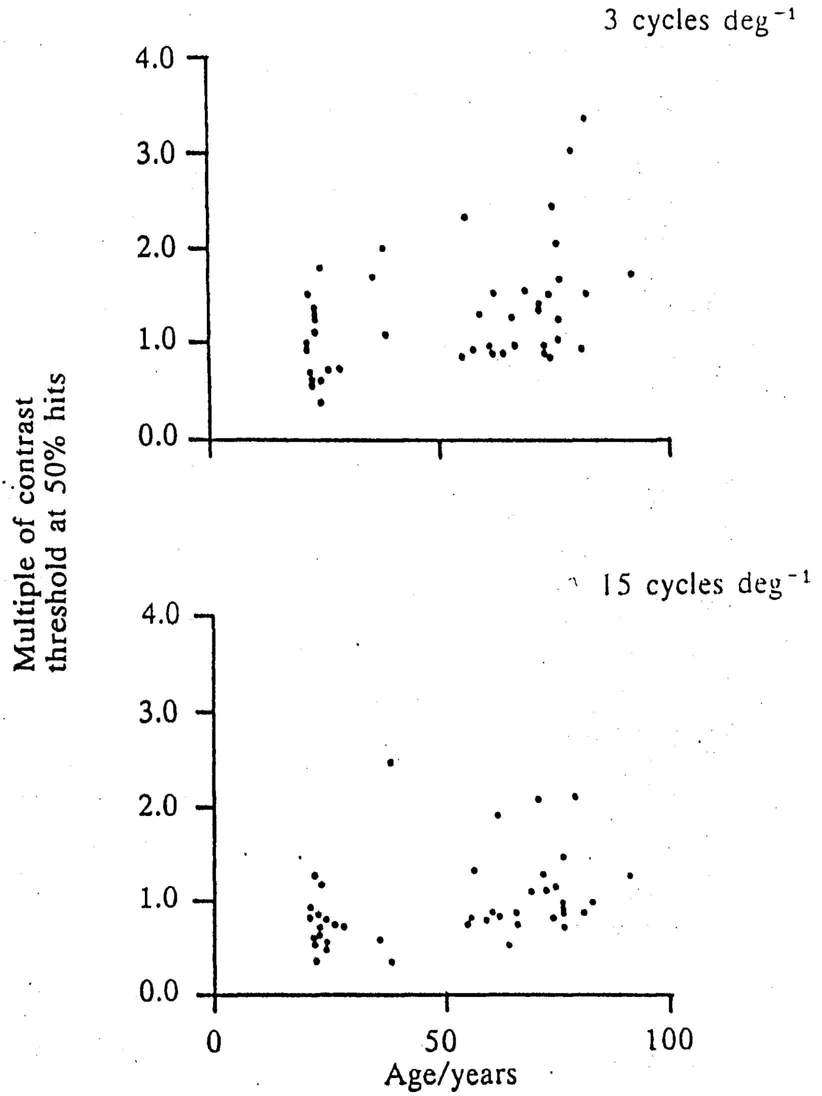


FIGURE 12. Multiple of contrast threshold which gave a 50% hit rate in the detection task is compared with age.

significantly higher than in young where it was 1.09 ±0.11 ($p<0.05$). In the very old subjects the multiple was 1.62 ±0.18, again significantly higher than in young ($p<0.02$).

Using a 15 c/deg stimulus, the multiple of contrast threshold which produced a 50% hit rate was 0.81 ±0.11 in young subjects and 1.07 ±0.08 in old subjects; the difference was marginally significant ($0.05<p<0.1$). If the young group is compared to the very old group (for which the multiple in question was 1.18 ±0.12) then the difference <u>is</u> significant ($p<0.05$).

The mean multiples of threshold which gave a 25% and a 75% hit rate were also calculated for young and old subjects at both 3 c/deg and 15 c/deg. At the lower of the two spatial frequencies the mean multiple of threshold at 25% hits was 0.91 ±0.09 in young, significantly lower than in old where the value was 1.43 ±0.19 ($p<0.01$). At 75% hits, the multiple of contrast threshold needed by young subjects was 1.27 ±0.13 while in old people it was higher, 1.74 ±0.17, although only marginally significantly so ($0.05<p<0.1$).

At 15 c/deg, the multiple of threshold which gave a 25% hit rate was 0.63 ±0.08 in young and 0.95 ±0.08 in old; the difference was significant ($p<0.05$). For a 75% hit rate, the multiple required by young subjects was 0.88 ±0.08; this was significantly lower ($p<0.05$) than that of old subjects where the multiple was 1.21 ±0.1.

A rough check was made on the validity of using multiples of contrast threshold as comparators (i.e. will a stimulus of, for instance, 1.5x threshold be psychophysically equivalent in different subjects given that their original thresholds might have been, in absolute terms, very different?).

The mean values of contrast multiples calculated above were plotted in a graph of hit rate vs contrast multiple and a line drawn through the points by eye (Fig. 13). There were no obvious differences in the slopes of young and old subjects. Had the slope of old subjects been, for example, shallower than that of young subjects then this might have suggested that an identical increase in stimulus contrast (in terms of multiple of threshold) would have a less profound effect on old people than it did in young. The similarities of the slopes serves in some small way to vindicate the use of contrast multipliers.

Hit rate

At contrast threshold and for both spatial frequencies there appeared to be a trend towards a reduction in hit rate in the older groups. When statistically analysed there were found to be marginally significant differences in detection rate between the young and the old group. At 3 c/deg the young group had a mean hit rate of 0.68 ±0.09 while the old group had a hit rate of 0.47 ±0.07 ($0.05<p<0.1$). At 15 c/deg the young group's hit rate was 0.79 ±0.07 while that of the old group was 0.63 ±0.06 ($0.05<p<0.1$).

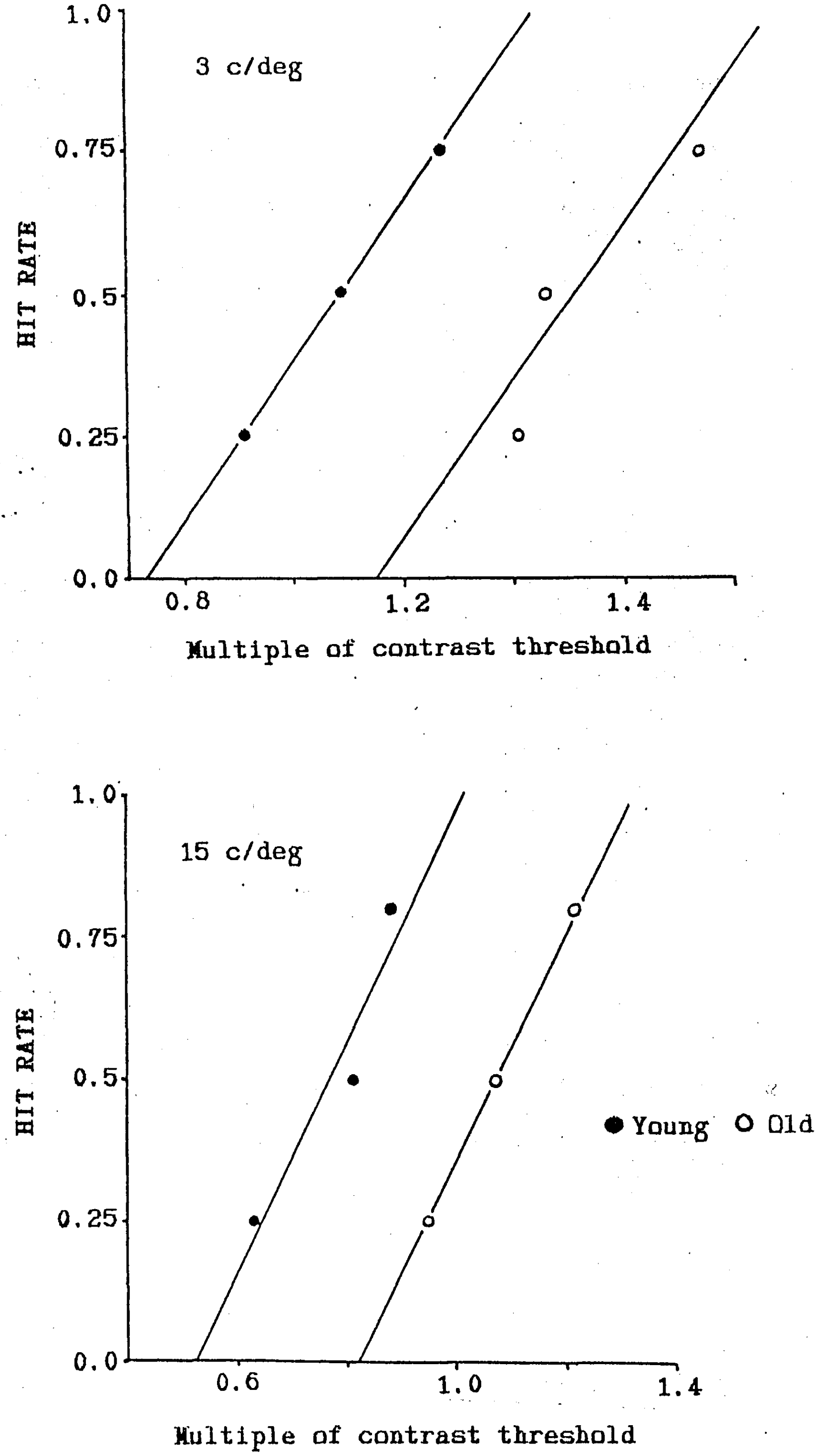


FIGURE 13. Mean multiple of contrast threshold at 3 c/deg and 15 c/deg for young and old subjects at 25%, 50% and 75% hit rate. Slopes drawn by eye.

When a comparison of hit rate was made at 3 c/deg between the young and the very old group (0.39 ±0.12) then the difference was marginally significant (0.05<p<0.1). At 15 c/deg the very old group's hit rate (0.49 ±0.11) was significantly lower than that of the young group (p<0.01).

False alarm rate

At contrast threshold and with both a 3 c/deg and 15 c/deg stimulus there were no consistent differences in false alarm rate between young and old subjects. For the lower spatial frequency the mean false alarm rate was 0.12 ±0.03 in young and 0.05 ±0.02 in old, a difference of marginal significance (0.05<p<0.1). The very old group had a mean false alarm rate of 0.06 ±0.03, not significantly different from that of young (p>0.2).

For the higher spatial frequency the mean false alarm rate in the young group was 0.06 ±0.02 while in the old group it was 0.09 ±0.03 (p>0.4). In the very old group the false alarm rate was 0.14 ±0.04, the difference from young being of marginal significance (0.05<p<0.1).

At 50% hits the mean false alarm rate at 3 c/deg in the young group was 0.16 ±0.03, marginally significantly different from that of the old group (0.09 ±0.02; 0.05<p<0.1) and not significantly different from that of the very old group (0.09 ±0.02; p>0.1). At 15 c/deg the mean false alarm rate was 0.08 ±0.02 in the young group and 0.08 ±0.02 in the old group (p>0.9); the false alarm rate in the very old group was 0.05 ±0.02, not significantly different from that of the young (p>0.3).

Since both d′ and β are calculated with false alarm rates of zero excluded, a comparison of the mean false alarm rates in young and old *omitting* zero false alarm rates was also made.

For 3 c/deg, at contrast threshold the young group's false alarm rate was 0.13 ±0.03, not significantly different from that of the old group where the rate was 0.08 ±0.02 ($p>0.2$) nor that of the very old group where the rate was 0.13 ±0.03 ($p>0.4$). The same was true for 15 c/deg: in young subjects the false alarm rate was 0.09 ±0.02 while in old subjects it was 0.12 ±0.03 ($p>0.4$). In the very old group the false alarm rate was 0.15 ±0.05 (not significantly different from young; $p>0.2$).

At 50% hits, the young group's false alarm rate at 3 c/deg (0.21 ±0.03) *was* significantly higher than both that of the old group (0.10 ±0.02; $p<0.01$) and that of the very old group (0.11 ±0.02; $p<0.05$). At 15 c/deg, in the young group the false alarm rate was 0.16 ±0.03 while in the old group it was 0.11 ±0.02; the difference was not significant ($p>0.1$). Neither was it when the young group was compared with the very old group where the latter's false alarm rate was 0.12 ±0.03 ($p>0.4$).

Contrast sensitivity at 50% hits; an alternative measurement

If the 3 c/deg stimulus contrast which gave a 50% hit rate is taken as an alternative measure of threshold and converted into a contrast sensitivity measurement then the difference between groups is still present (Fig. 14). In the younger subjects, a paired *t*-test revealed no significant difference in the log

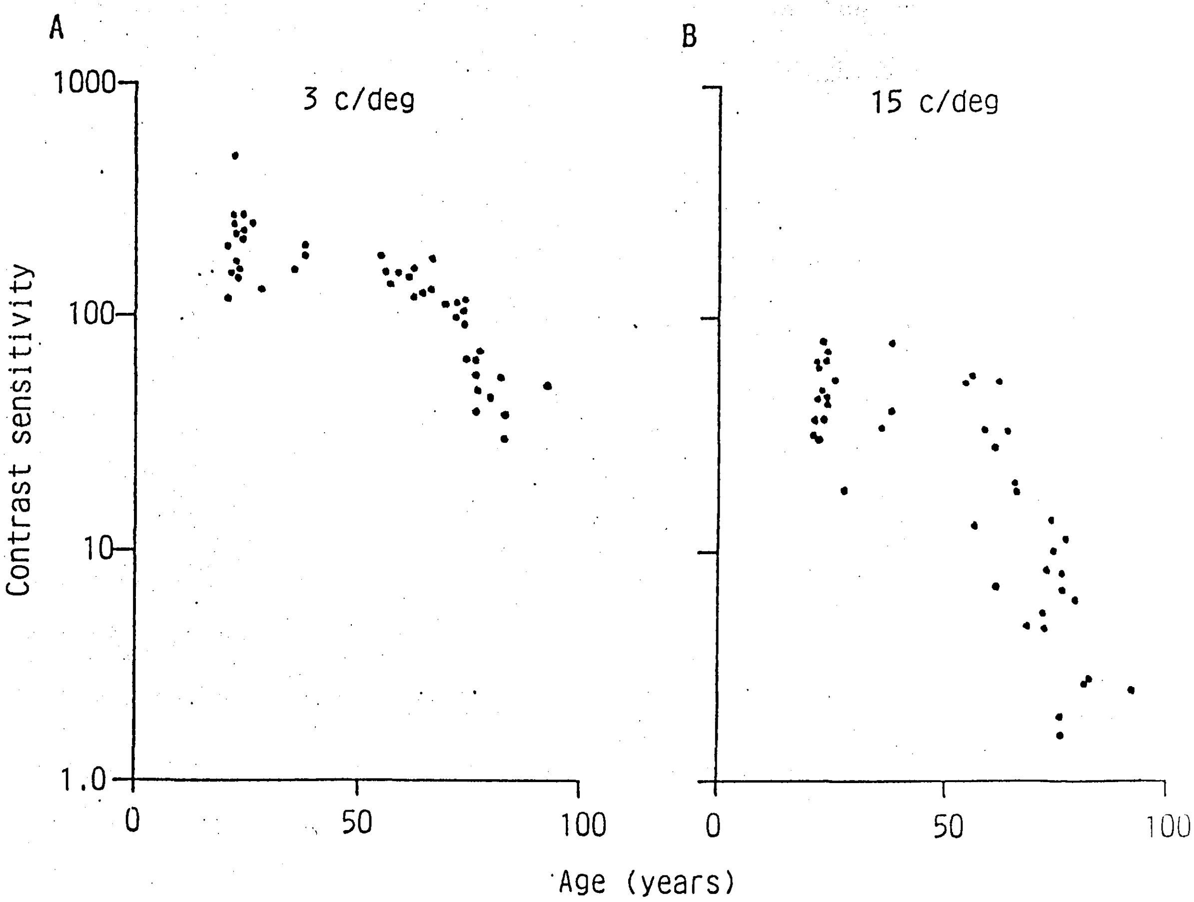


FIGURE 14. Contrast sensitivity (logarithmic units) determined by the 50% hits method for 3 c/deg (A) and 15c/deg (B) at different ages.

contrast sensitivities obtained using the ascending method and the alternative '50% hits' method (2.29 ±0.05 and 2.29 ±0.04 respectively; $p>0.9$). For the older subjects, on the other hand, the log contrast sensitivity derived from the 50% hits threshold was significantly lower than that obtained using the ascending method (1.94 ±0.04 and 2.06 ±0.04 respectively; $p<0.01$). The latter was also true of the very old group; 1.79 ±0.05 for the 50% hits method, 1.95 ±0.04 for the ascending method ($p<0.01$).

Since the 50% hits method reveals a greater difference in contrast sensitivity between young and old than does the ascending method, this would seem to indicate that, at this spatial frequency, the latter method in fact underestimates the ageing changes (Fig. 15).

With the higher spatial frequency pattern, the ascending method had shown that both of the older groups had significantly lower contrast sensitivities than the younger group. However, this difference was not further accentuated by the use of the 50% hits method (Figs. 14 and 15). In young subjects, log contrast sensitivity (ascending) was 1.51 ±0.06 while log contrast sensitivity (50% hits) was 1.66 ±0.04 ($p>0.1$). For the old group the former was 0.95 ±0.08 while the latter was 0.97 ±0.1 ($p>0.7$). In the very old group the respective values were 0.71 ±0.08 and 0.66 ±0.09 ($p>0.2$).

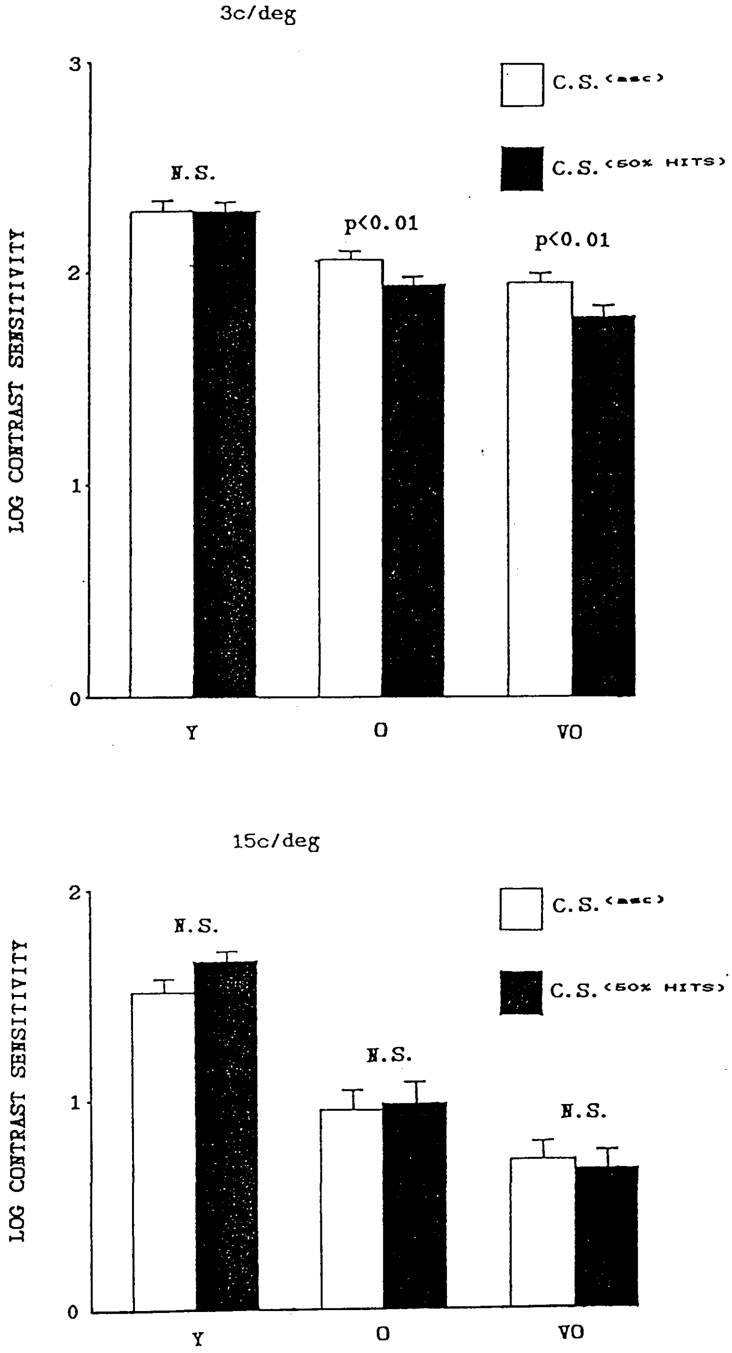


FIGURE 15. Mean log contrast sensitivity determined by both the ascending method and the 50% hits method for young (Y), old (O) and very old (VO) subjects. Significance values refer to differences between the two methods for each age group.

Sex differences

Contrast sensitivity for males and females were not significantly different at either 3 c/deg or 15 c/deg for either ascending or 50% hits method in either young or old groups ($p>0.3$ in all cases).

Sensitivity and criterion; effects of contrast

From the individual graphs of d′ against contrast multiple plotted for each subject it was clear that the general trend was for sensitivity to rise with increasing contrast. This was to be expected given the manner in which hit rate varied with contrast multiple and given that false alarm rates tended to stay relatively low and constant across the range of multiples tested.

From inspection of the individual graphs of β against contrast multiples it was not obvious that there was any trend with changing stimulus contrast.

Given that subjects of different ages operated over different ranges of contrast multiple and in order to facilitate both graphical and statistical analysis of the effects of contrast on criterion and sensitivity, the results were 'normalized' with respect to the multiple of contrast threshold which for each individual subject yielded a 50% hit rate. The multiple in question (irrespective of its absolute value) was assigned a ranking of zero; each step above and below this common point of reference corresponded to a rise or fall of 0.1x contrast threshold. For example, if one subject achieved a 50% correct detection rate at 1.2x threshold then this point on the graph would be regarded as zero; 1.3x threshold would be assigned the value of 1; 1.1x threshold would be given the value of -1 and so on.

Figures 16 and 17 show the d′ and β values plotted in this manner for all subjects. It is apparent that the grouped data shows a similar pattern to that of the individual results. For d′, at both spatial frequencies linear regression analyses showed that there is a significant rise in value with increasing contrast (3 c/deg: $r=0.61$, $p<0.01$; 15 c/deg: $r= 0.54$, $p< 0.01$). A similar analysis showed that β did not vary significantly with contrast multiple at either 3 c/deg ($r=-0.12$; $p>0.1$) or at 15 c/deg ($r=-0.15$; $p=0.1$).

The trend (or lack of it) becomes even more apparent when the mean values of d′ and β are calculated for each multiple of contrast threshold (omitting those multiples with less than five data points) and represented graphically (Figs. 18 and 19).

Criterion: effects of spatial frequency

In order to ascertain whether the subject's criterion was influenced by the spatial frequency of the stimulus, the β scores attained at 3 c/deg were compared with those at 15 c/deg. This was done for the young and the old groups at both contrast threshold and 50% hits. In no instances was a significant difference observed ($p>0.1$).

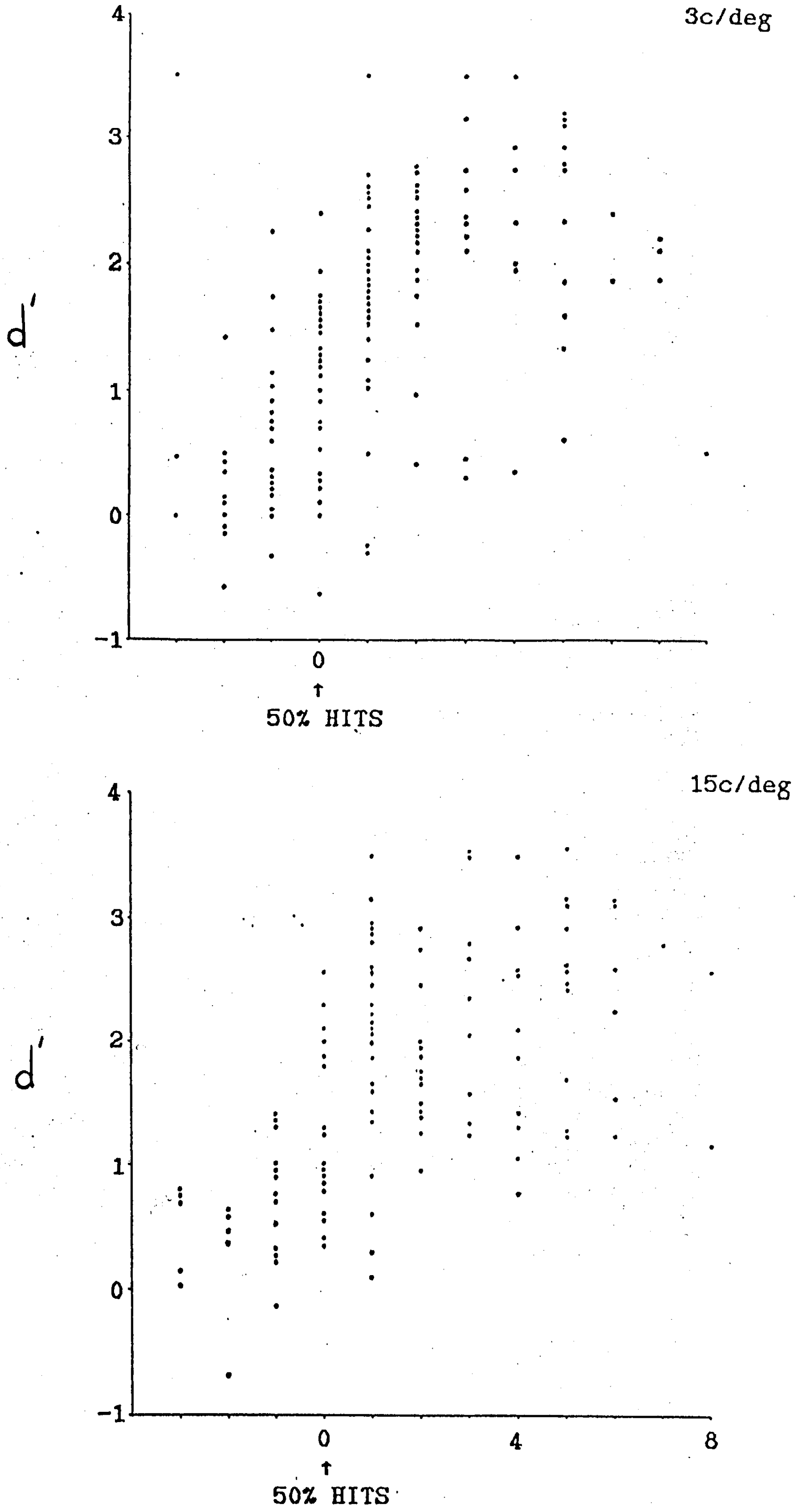


FIGURE 16. Sensitivity (d′) for 3 c/deg and 15 c/deg at increasing multiples of contrast threshold, the latter 'normalised' with respect to the multiple of threshold which gave a 50% hit rate. Subjects of all ages are represented (See text for details).

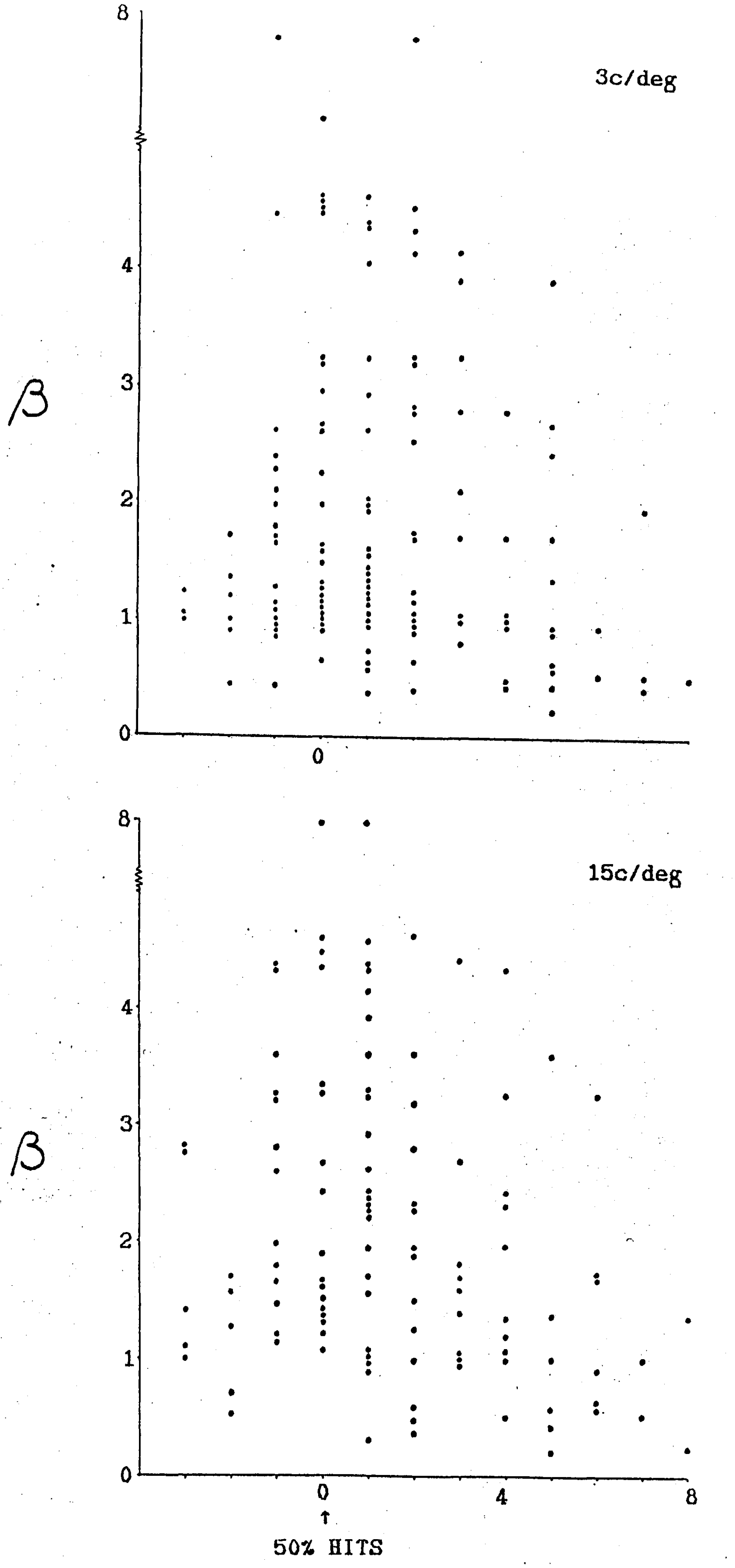


FIGURE 17. Criterion (β) for 3 c/deg and 15 c/deg at increasing multiples of contrast threshold, the latter 'normalised' as in Fig. 16.

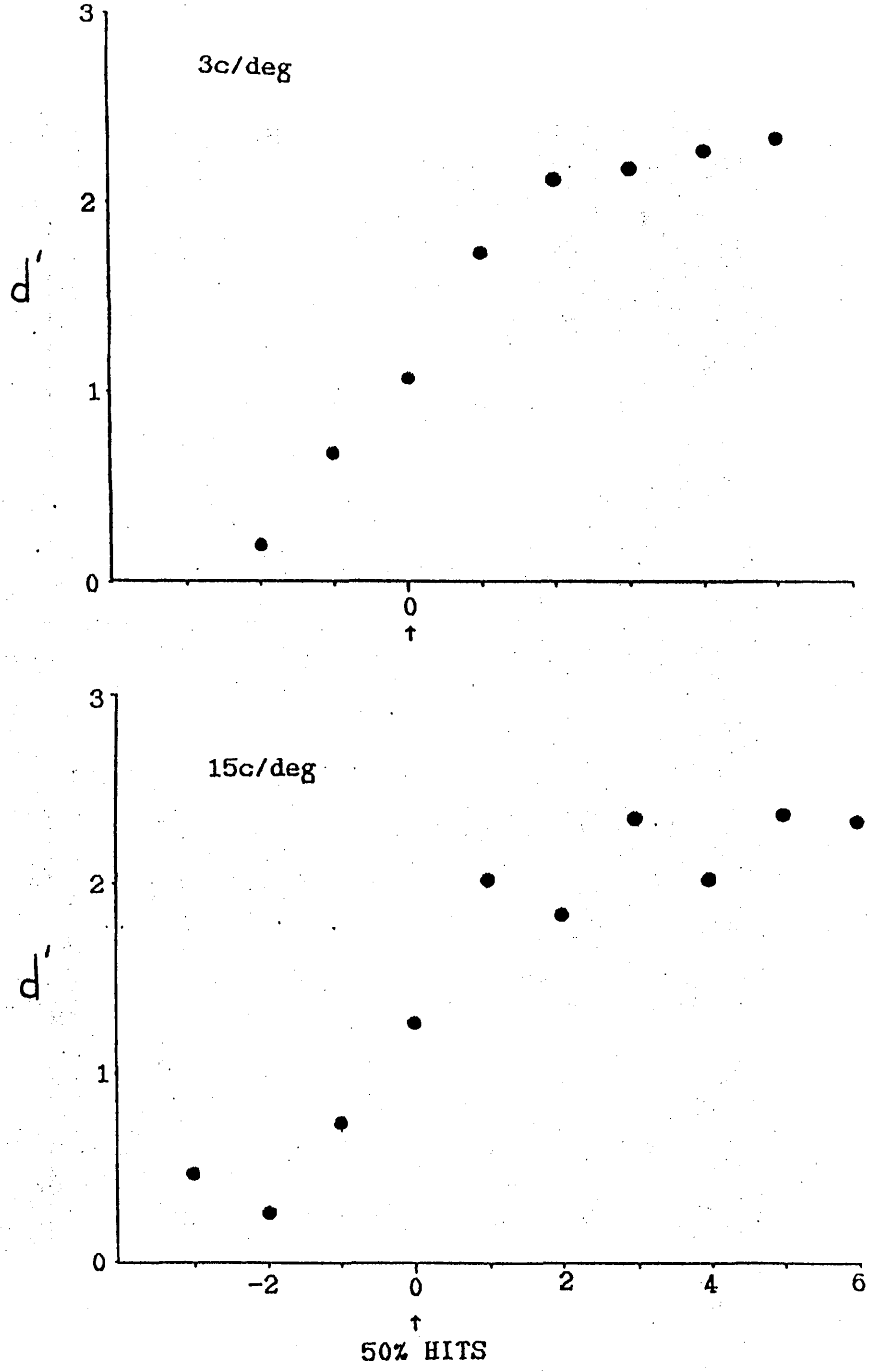


FIGURE 18. Mean sensitivity (d′) for 3 c/deg and 15 c/deg at increasing multiples of contrast threshold, the latter 'normalised' as in Fig. 16.

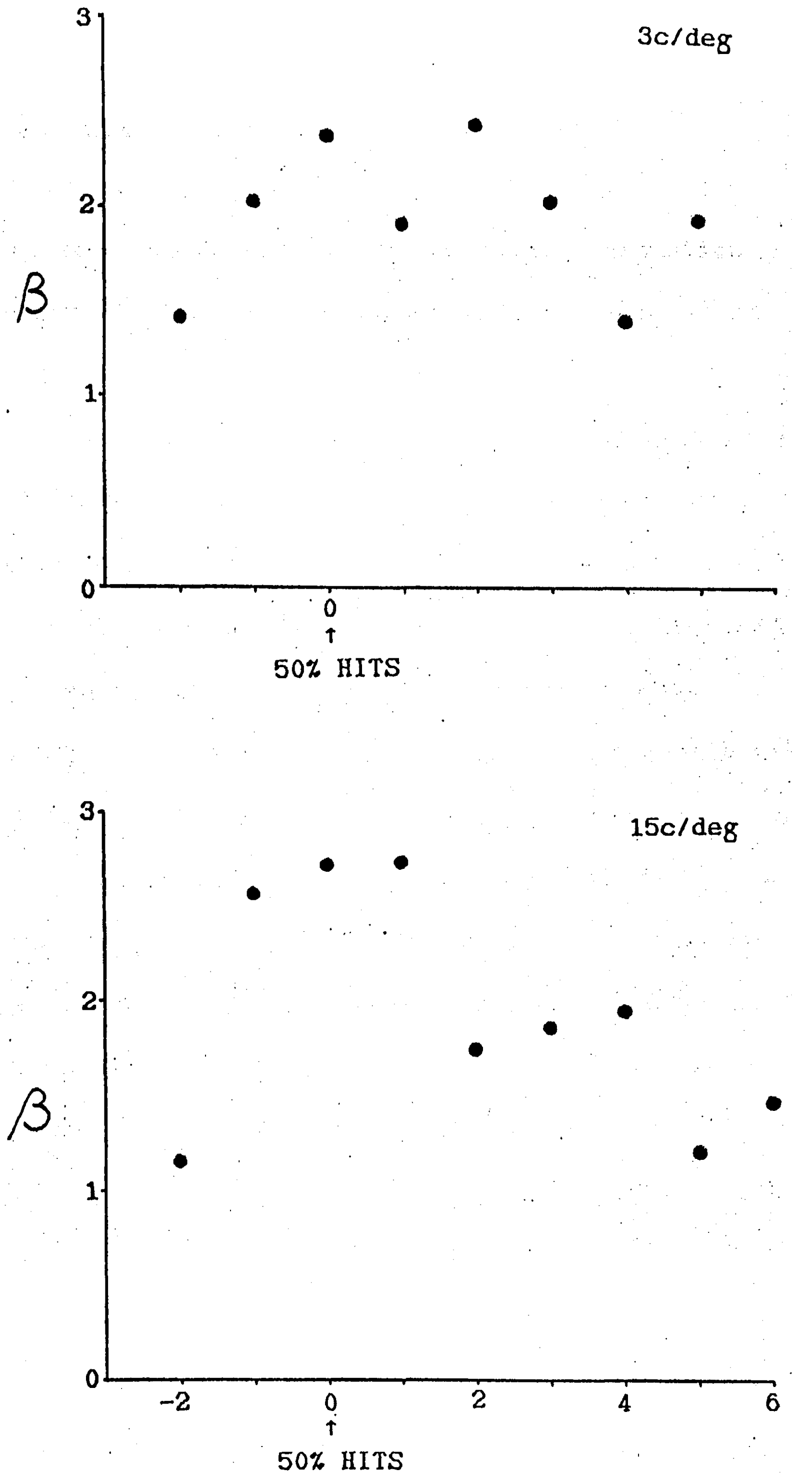


FIGURE 19. Mean criterion (β) for 3 c/deg and 15 c/deg at increasing multiples of contrast threshold, the latter 'normalised' as in Fig. 16.

Effects of age

(i) Sensitivity (d′)

Data was widely scattered and visual inspection did not give any clear indication of age-related changes in sensitivity (Fig. 20).

At contrast threshold and using a 3 c/deg grating pattern, the mean d′ score of young subjects was 1.57 ±0.44 while that of old subjects was 1.49 ±0.33. The difference was not statistically significant ($p>0.8$). For very old subjects d′ was 0.99 ±0.47, not significantly different from young subjects ($p\simeq 0.4$). However, at the 50% hit rate the value of d′ was significantly higher in the old group (1.40 ±0.12) than in the young group (0.88 ±0.14) ($p<0.01$). In the very old group d′ was 1.43 ±0.17, the difference from young again being significant ($p<0.05$) (see Table 1).

With a 15 c/deg stimulus at contrast threshold, d′ was 2.13 ±0.35 in young subjects and 1.53 ±0.23 in old subjects, the difference not being significant ($p>0.1$). The d′ score of the very old group was 1.29 ±0.3, marginally significantly different from the young group ($0.05<p<0.1$). At the 50% hit rate, d′ in young subjects was 1.25 ±0.18 while that in old subjects was 1.46 ±0.15 (no significant difference, $p>0.3$). For the very old group d′ at 50% hits was 1.32 ±0.19, not significantly different from young ($p>0.8$) (see Table 1).

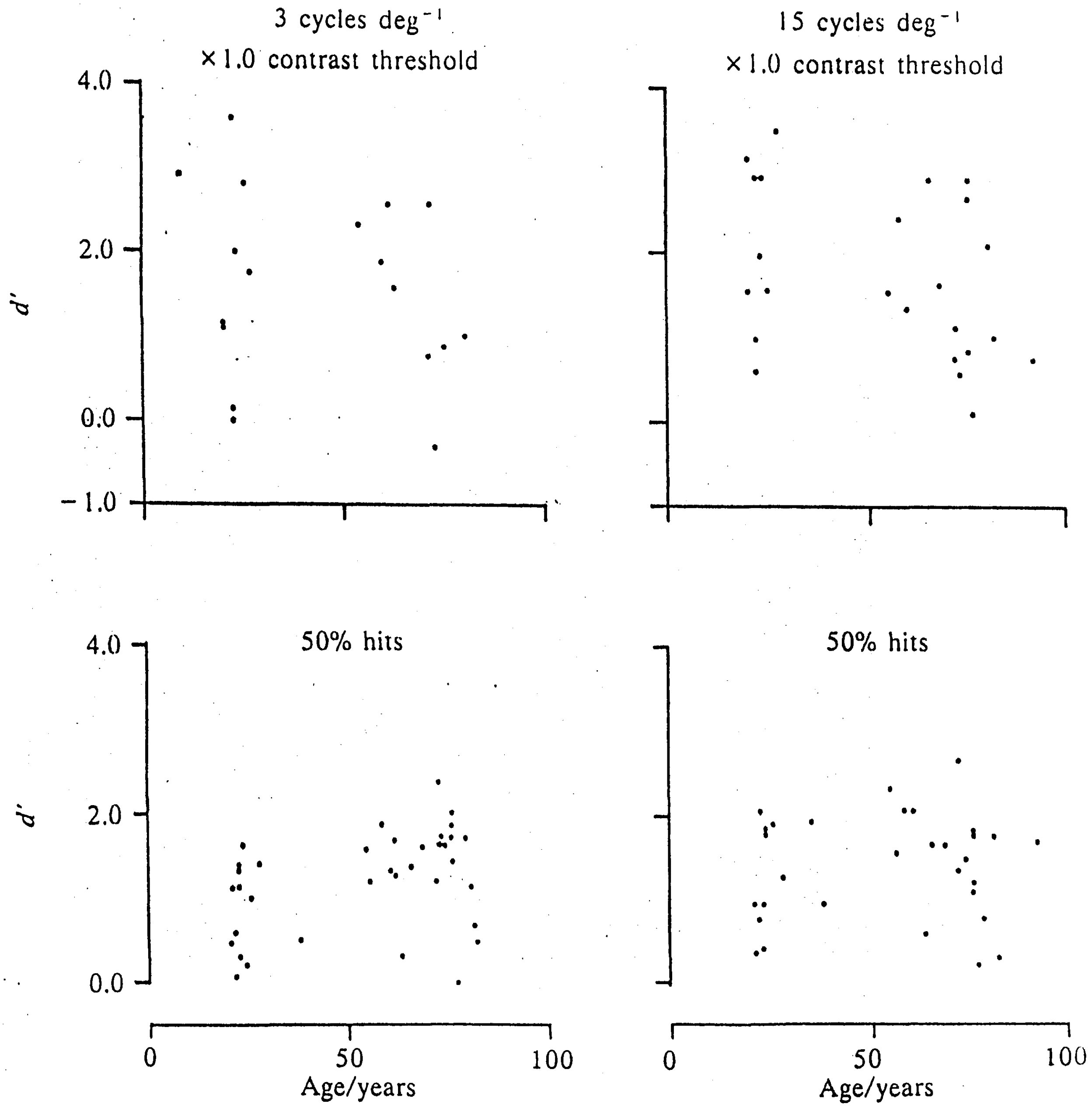


FIGURE 20. Sensitivity (d') for 3 c/deg and 15 c/deg at 1.0x contrast threshold (top) and at 50% hit rate (bottom), at different ages.

TABLE 1. Summary table showing mean values of sensitivity (d′) for young (Y), old (O) and very old (VO) subjects.

		Y	O	VO
	0.8x threshold	1.44	0.99	-
3c/deg	1.0x threshold	1.57	1.49	0.99
	1.2x threshold	1.90	2.37	2.64
	50% hits	0.88	1.40*	1.43*
	0.8x threshold	1.55	1.29+	0.95
15c/deg	1.0x threshold	2.13	1.53	1.29
	1.2x threshold	2.13	1.99	1.67
	50% hits	1.25	1.46	1.32

Significance values refer to differences when old and very old groups were compared with young (* $p<0.05$; + $0.05<p<0.1$; remainder $p>0.1$).

(ii) Criterion (β)

Data was again widely scattered and no obvious age-related trends were apparent by visual inspection (Fig. 21).

Statistical comparisons showed that there was only marginally significant difference between the β scores of young and old subjects with a 3 c/deg pattern at contrast threshold (1.45 ±0.26 and 3.07 ±0.8, respectively; $0.05<p<0.1$). The β score of the very old group was 2.45 ±0.44, again the difference from young being marginally significant ($0.05<p<0.1$). At the 50% hit rate β was significantly higher in old subjects (3.3 ±0.43 compared with 1.82 ±0.24 in younger subjects; $p<0.01$). The β score for the very old subjects was 3.2 ±0.57, again significantly higher than the younger subjects ($p<0.05$) (see Table 2).

With a 15 c/deg stimulus presented at contrast threshold the β score attained by young subjects was 1.72 ±0.16. This was not significantly different from either the β score of old subjects (2.28 ±0.31, $p>0.2$) or that of very old subjects (2.12 ±0.41, $p>0.3$). At the 50% hit rate the same was true; the β score of young subjects (3.2 ±0.64) was not significantly different from that of old subjects (3.48 ±0.46, $p>0.7$) nor that of very old subjects (2.79 ±0.4, $p>0.5$) (see Table 2).

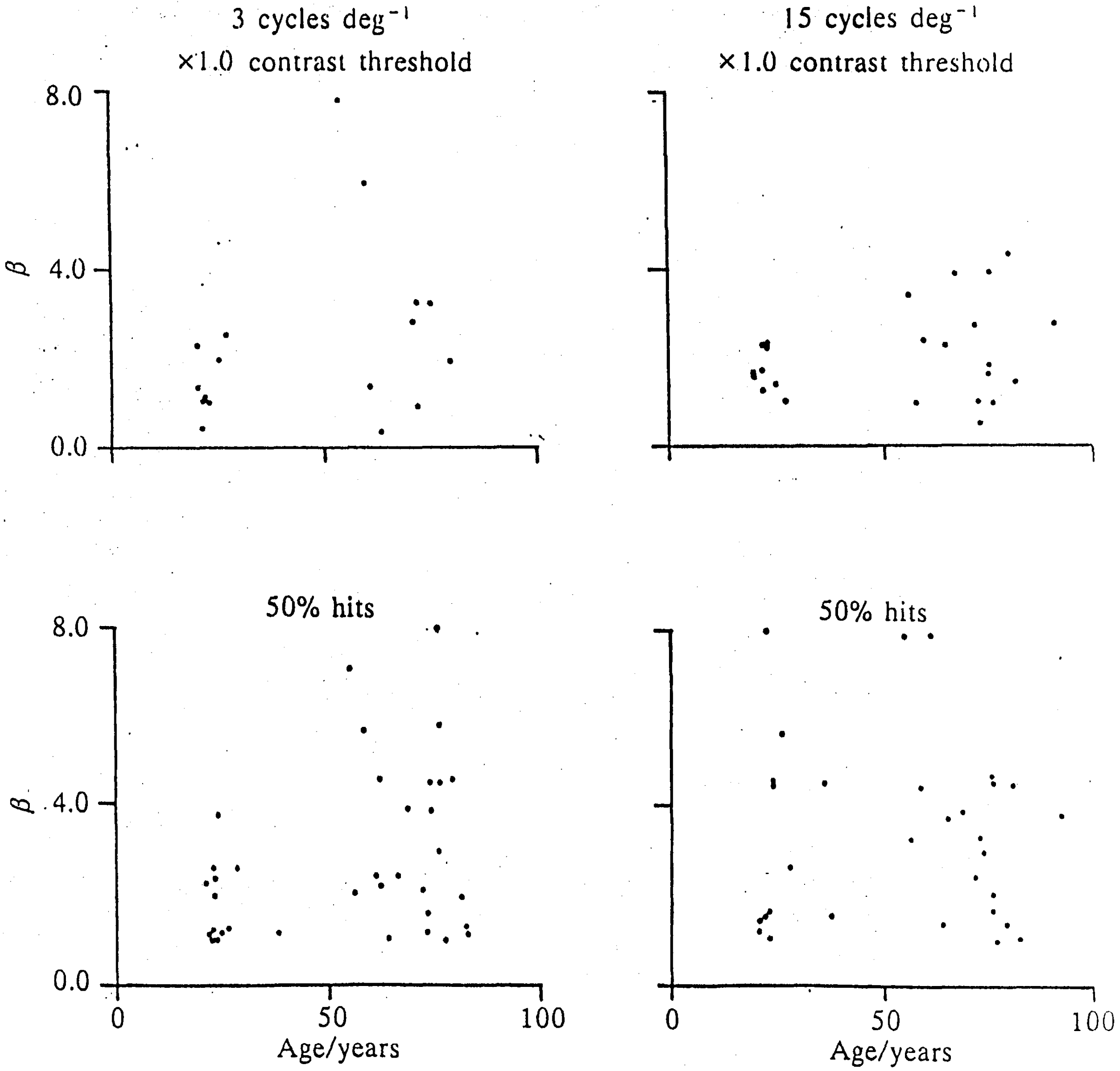


FIGURE 21. Criterion (β) for 3 c/deg and 15 c/deg at 1.0x contrast threshold (top) and at 50% hit rate (bottom), at different ages.

TABLE 2. Summary table showing mean values of criterion (β) for young (Y), old (O) and very old (VO) subjects.

		Y	O	VO
	0.8x threshold	1.43	3.33	-
3c/deg	1.0x threshold	1.45	3.07^{+}	2.45^{+}
	1.2x threshold	1.1	2.26	1.69
	50% hits	1.82	3.3^{*}	3.2^{*}
	0.8x threshold	2.78	3.08	2.43
15c/deg	1.0x threshold	1.72	2.28	2.12
	1.2x threshold	2.46	2.28	2.5
	50% hits	3.2	3.48	2.79

Significance values refer to differences when old and very old groups were compared with young (* $p<0.05$; + $0.05<p<0.1$; remainder $p>0.1$).

(iii) Percentage bias

The alternative method of calculating criterion as percentage bias (Hodos, 1970) was derived. Statistical comparisons were made with the Mann-Whitney test.

At 3 c/deg, bias was higher at contrast threshold in both old and very old subjects (median percentage bias of 95 in both cases) than in young subjects (median bias of 42); the difference was significant ($p<0.01$), indicating a stricter criterion adopted by old subjects. At 50% hits the median bias in both groups of old subjects was 92 while that in young subjects was 79, marginally significantly different ($0.05<p<0.1$) (Fig. 22 and Table 3).

At 15 c/deg and contrast threshold median bias was significantly higher in old (a value of 80) than in young subjects (50), ($p<0.05$). In the very old group, a value of 80 was <u>not</u> significantly different from that of young ($p>0.1$). At 50% hits, bias was not significantly different between young and old subjects (respectively 92 and 90, $p>0.7$); neither was there any difference between young and very old (88; $p>0.4$) (Fig. 22 and Table 3).

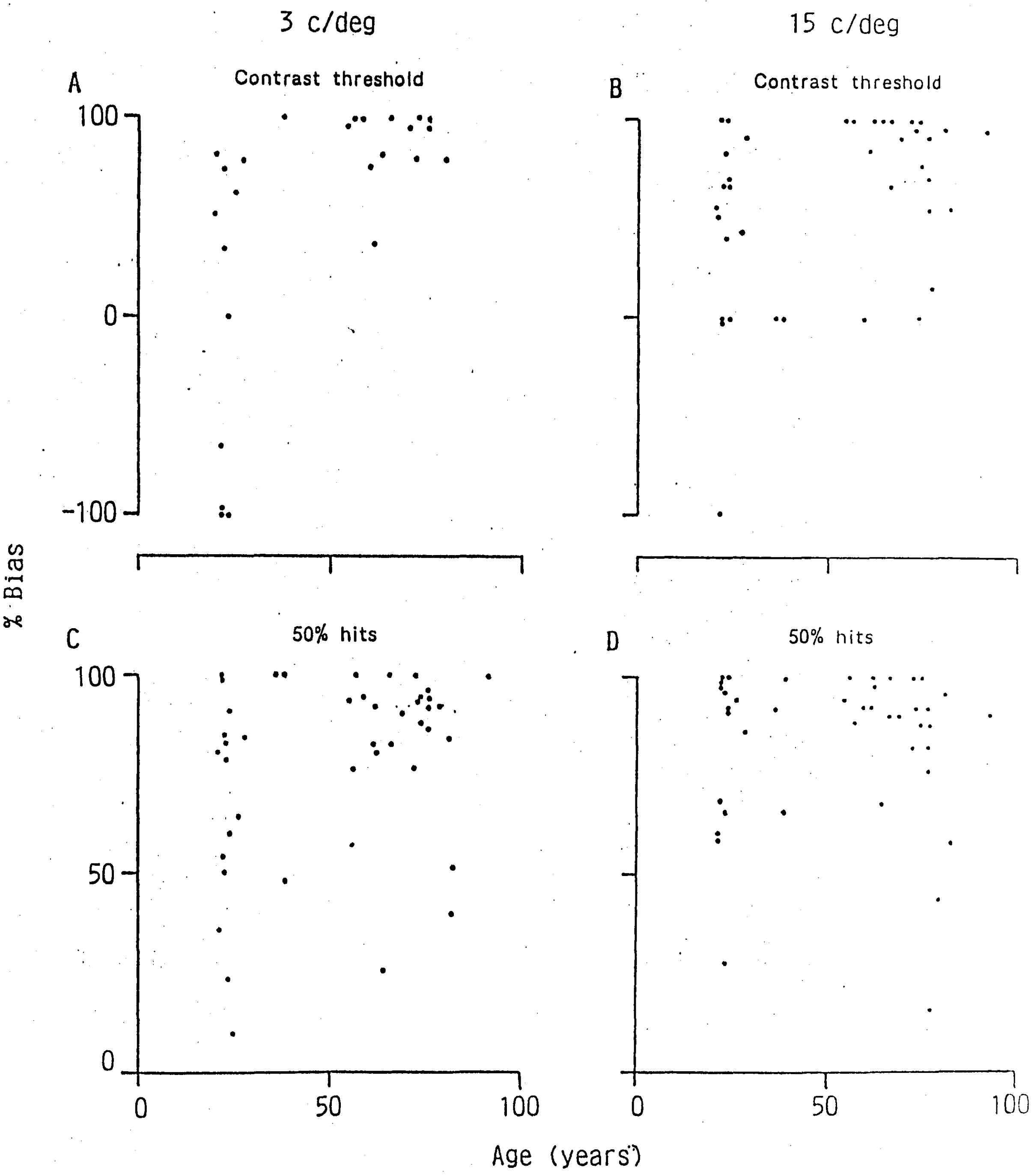


FIGURE 22. Criterion (% bias) at 3 c/deg and 15 c/deg for contrast threshold (A & B) and 50% hit rate (C & D) at different ages.

TABLE 3. Summary table showing median values of percentage bias for young (Y), old (O) and very old (VO) subjects.

		Y	**O**	**VO**
	0.8x threshold	42.5	94.5*	-
3c/deg	1.0x threshold	42.0	95.0*	95.0*
	1.2x threshold	-24.5	75.0*	71.0
	50% hits	79.0	92.0+	92.0+
	0.8x threshold	79.0	95.5+	94.0
15c/deg	1.0x threshold	50.0	80.0*	80.0
	1.2x threshold	0.0	33.0+	73.0*
	50% hits	92.0	90.0	88.0

Significance values refer to differences when old and very old groups were compared with young (* $p<0.05$; + $0.05<p<0.1$; remainder $p>0.1$).

(iv) Additional comparisons of d', β and percentage bias

These were done for both spatial frequencies at 0.8x and 1.2x contrast threshold. As before, comparisons of d' and β were made with the *t*-test while comparison of percentage bias were made with the Mann-Whitney test.

3 c/deg

(1) At 0.8x threshold mean d' was 1.44 ±0.47 in the young group, not significantly different from that of the old group (0.99 ±0.33) ($p>0.4$) (Fig. 23).

At the same contrast, mean β was 1.43 ±0.22 for the young subjects, while for the old subjects it was 3.33 ±0.99, the difference not being significant ($p>0.1$) (Fig. 24).

Median percentage bias was 42.5 in young and 94.5 in old; the difference was significant ($p<0.01$) (Fig. 25).

(2) At 1.2x threshold d' had a mean value of 1.9 ±0.52 in the young, whereas for old subjects the mean d' score was 2.37 ±0.27. The difference was not significant ($p>0.3$) (Fig. 23).

The mean β at 1.2x threshold was 1.1 ±0.29 in the young and 2.26 ±1.92 in the old, not significantly different ($p>0.2$) (Fig. 24).

Median percentage bias was −24.5 in the young subjects while in the old subjects it was 75 (significantly higher; $p<0.05$) (Fig. 25).

15 c/deg

(1) At 0.8x contrast threshold the mean d' score in the young group was 1.55 ±0.29, not significantly different from the score of 1.29 ±0.34 attained by the old group ($p>0.5$) (Fig. 23).

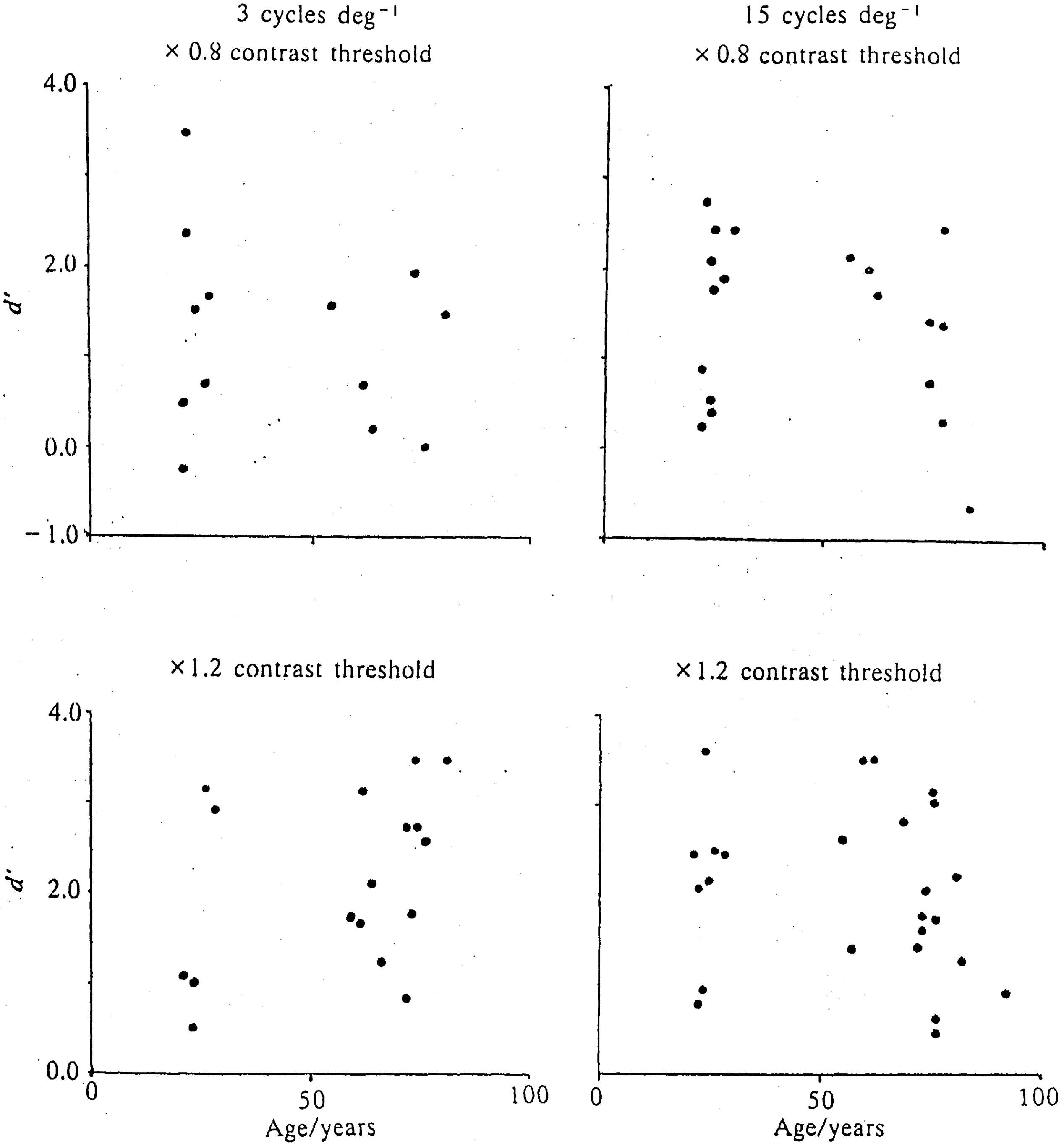


FIGURE 23. Sensitivity (d′) for 3 c/deg and 15 c/deg at 0.8x contrast threshold (top) and 1.2x contrast threshold (bottom), at different ages.

The number of points differ at each threshold multiple since every subject was not represented (see Pg. 74).

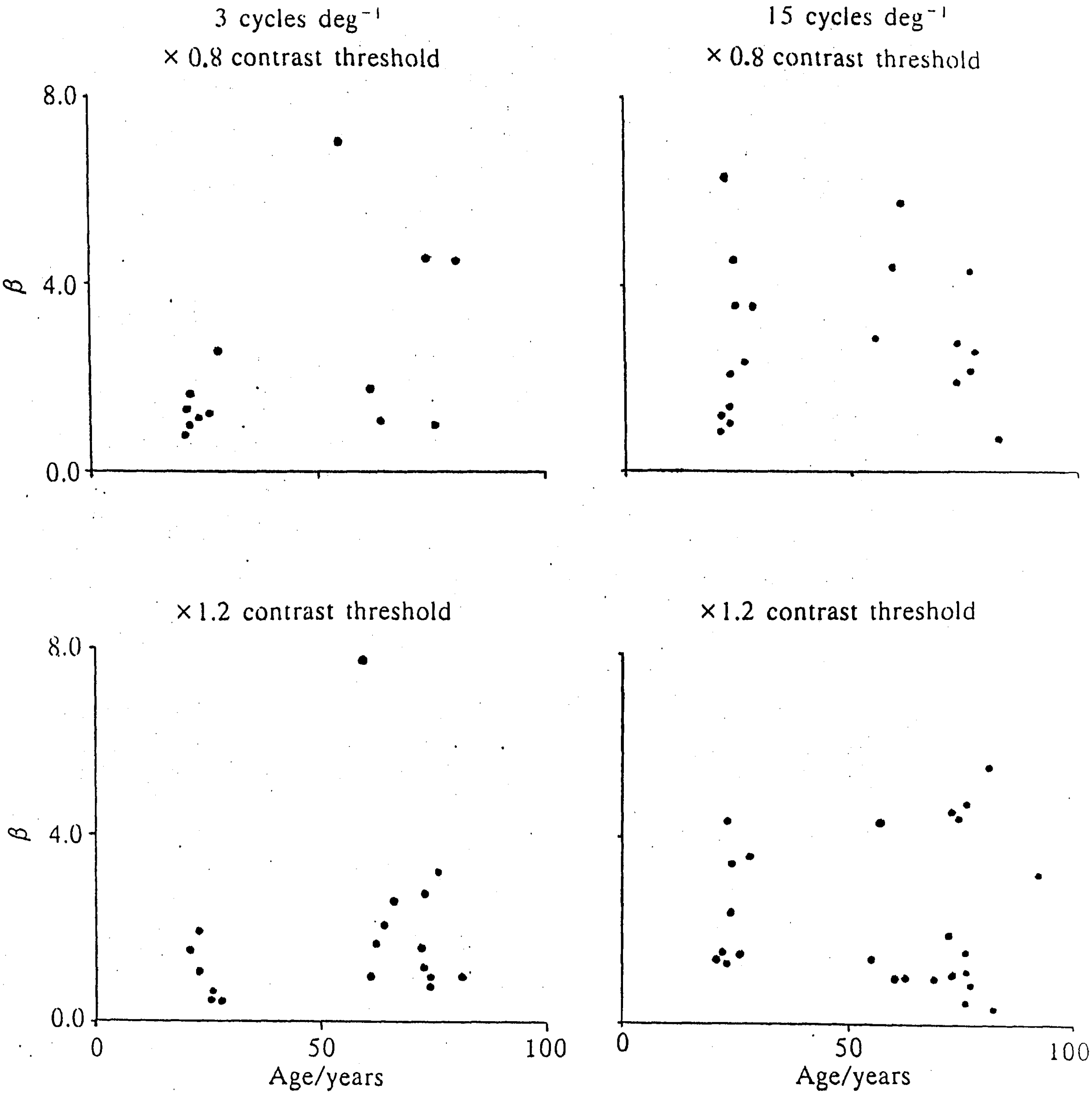


FIGURE 24. Criterion (β) for 3 c/deg and 15 c/deg at 0.8x contrast threshold (top) and 1.2x contrast threshold (bottom), at different ages.

The number of points differ at each threshold multiple since every subject was not represented (see Pg. 74).

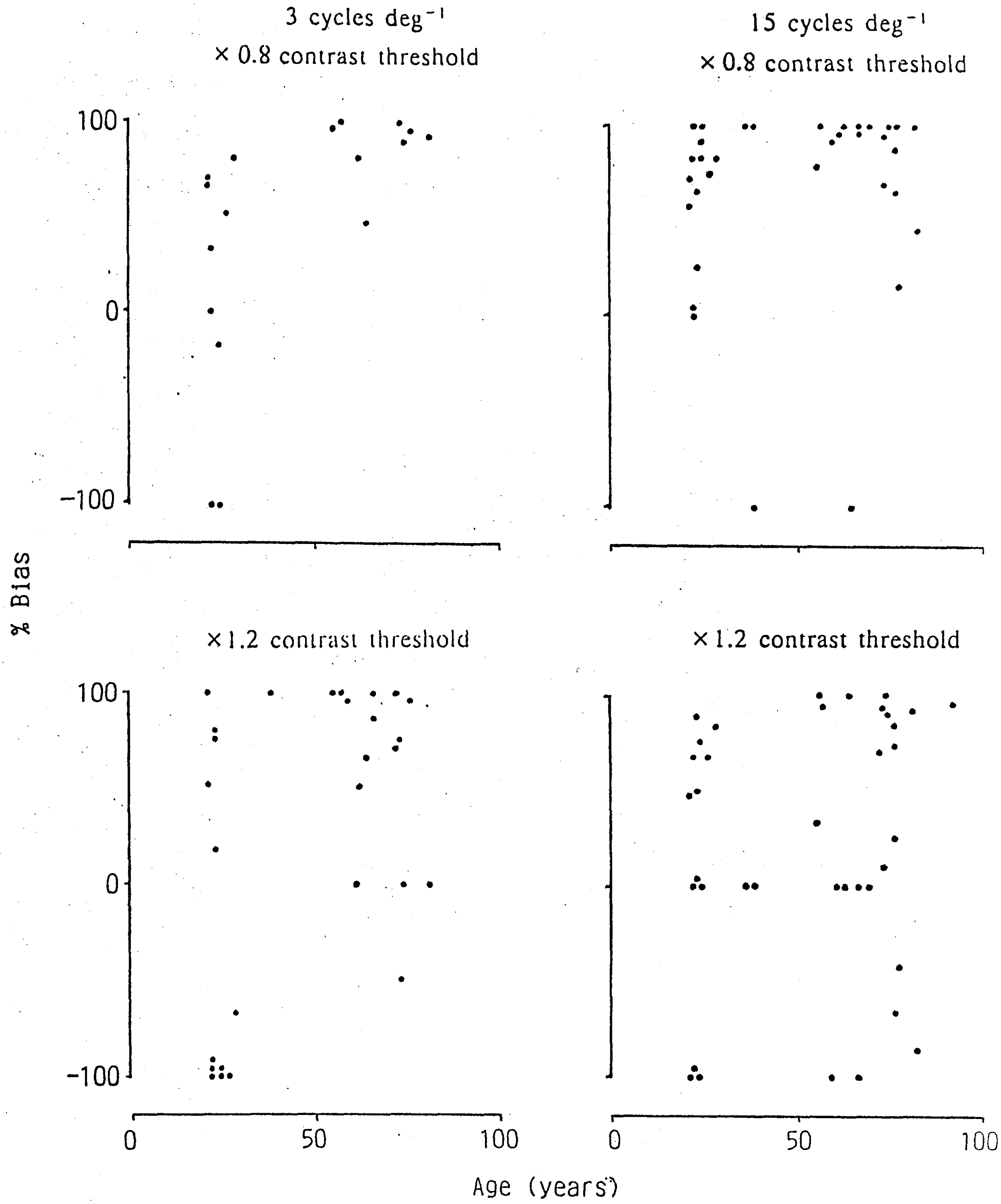


FIGURE 25. Percentage bias for 3 c/deg and 15 c/deg at 0.8x contrast threshold (top) and 1.2x contrast threshold (bottom), at different ages.

The number of points differ at each threshold multiple since every subject was not represented (see Pg. 74).

The mean β values at the same contrast were 2.78 ±0.55 in young and 3.08 ±0.51 in old. The difference was not significant ($p=0.7$) (Fig. 24).

Percentage bias in young was 79, not significantly different from the old group's median value of 95.5 ($0.1>p>0.05$) (Fig. 25).

(2) For 1.2x threshold, young subjects had a mean d′ value of 2.13 ±0.32 whereas for old subjects the mean score was 1.99 ±0.23. Again, the difference was not significant ($p>0.3$) (Fig. 23).

The β scores for young subjects at 1.2x threshold was 2.46 ±0.41; the β scores for old subjects was 2.28 ±0.43. The difference was not significant ($p>0.7$) (Fig. 24).

Median percentage bias in the young group was 0.0, marginally significantly different from that of the old group (33; $0.05<p<0.1$) (Fig. 25).

The young group and the *very old* group were also compared on the above measures (with the exception of d′ and β at 0.8x threshold for both spatial frequencies and percentage bias at 0.8x threshold for 3c/deg; in these instances, the small number of data points in the very old category precluded a statistical comparison). For d′ and β, in all cases, the pattern of no significant differences observed between young and old groups was mirrored closely in the comparison of young with very old. The same was true for percentage bias except in two instances: for 3c/deg at 1.2x threshold, where the median percentage bias in the very old group was 71, not significantly different from that of young (p>0.1); and for 15 c/deg at 1.2x threshold where the bias had a value of 73 in the very old group, significantly higher than that of the young group (p<0.05).

Table 4 gives a summary of the significant age differences in sensitivity, criterion and percentage bias.

TABLE 4. Summary table showing comparisons of sensitivity (d′), criterion (β) and percentage bias for young and old subjects.

		d′	β	% BIAS
3c/deg	0.8x threshold	N.S.	N.S.	*
	1.0x threshold	N.S.	+	*
	1.2x threshold	N.S.	N.S.	*[1]
	50% hits	*	*	+
15c/deg	0.8x threshold	+	N.S.	+
	1.0x threshold	N.S.	N.S.	*
	1.2x threshold	N.S.	N.S.	+[2]
	50% hits	N.S.	N.S.	N.S.

Significance values refer to differences between young and old groups; * p<0.05; + 0.05<p<0.1; N.S. Not significant.

[1] Not significant when young compared with very old;

[2] Significant when young compared with very old

Relationship of d', β, and percentage bias to contrast sensitivity.

At contrast threshold neither d′ nor β were significantly correlated with age. However, from Figure 10 it can be seen that, while contrast sensitivity was significantly reduced with age, there was a considerable variation of the data points which may be obscuring a more relevant correlation: that of log contrast sensitivity with d′ and β.

3 c/deg

A linear regression of log contrast sensitivity (ascending method) against d′ at contrast threshold was not significant (r=0.072). The same was true of log contrast sensitivity (50% hits method) against d′ at 50% hits (r=0.269). β also did not significantly vary with log contrast sensitivity (r=-0.148 for ascending method; r=-0.268 for 50% hits method) (p>0.1) (Figs. 26 and 27).

15 c/deg

Log contrast sensitivity did not vary significantly with d′ either for the ascending method (r=0.071) or for the 50% hits method (r=0.049). β did not vary significantly with either log contrast sensitivity (ascending) or log contrast sensitivity (50% hits) (r=-0.248 and r=-0.208, respectively) (p>0.1) (Figs. 26 and 27).

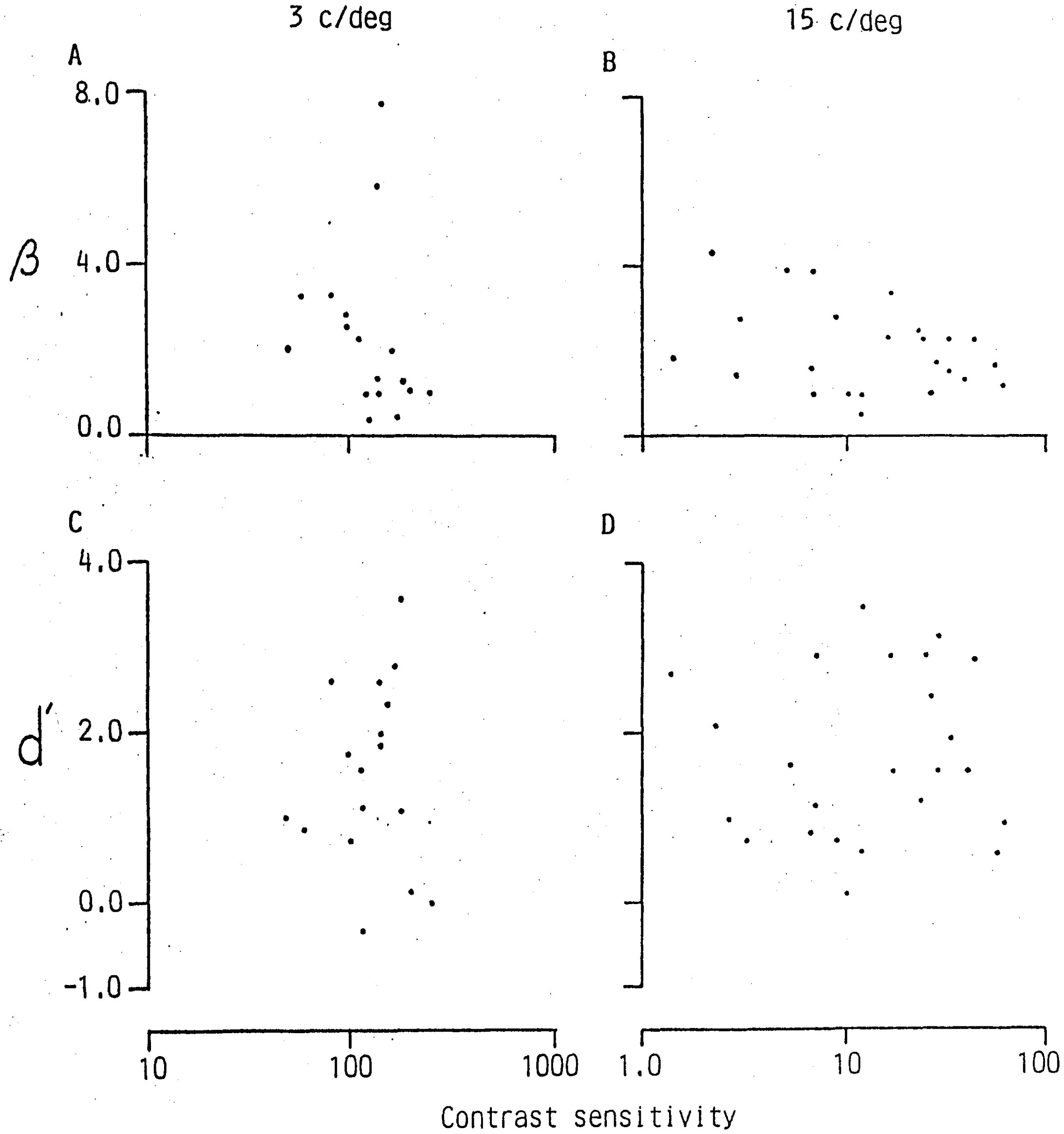


FIGURE 26. Correlation of criterion (β) (A & B) and sensitivity (d′) (C & D) at contrast threshold against contrast sensitivity (logarithmic units) determined by ascending method.

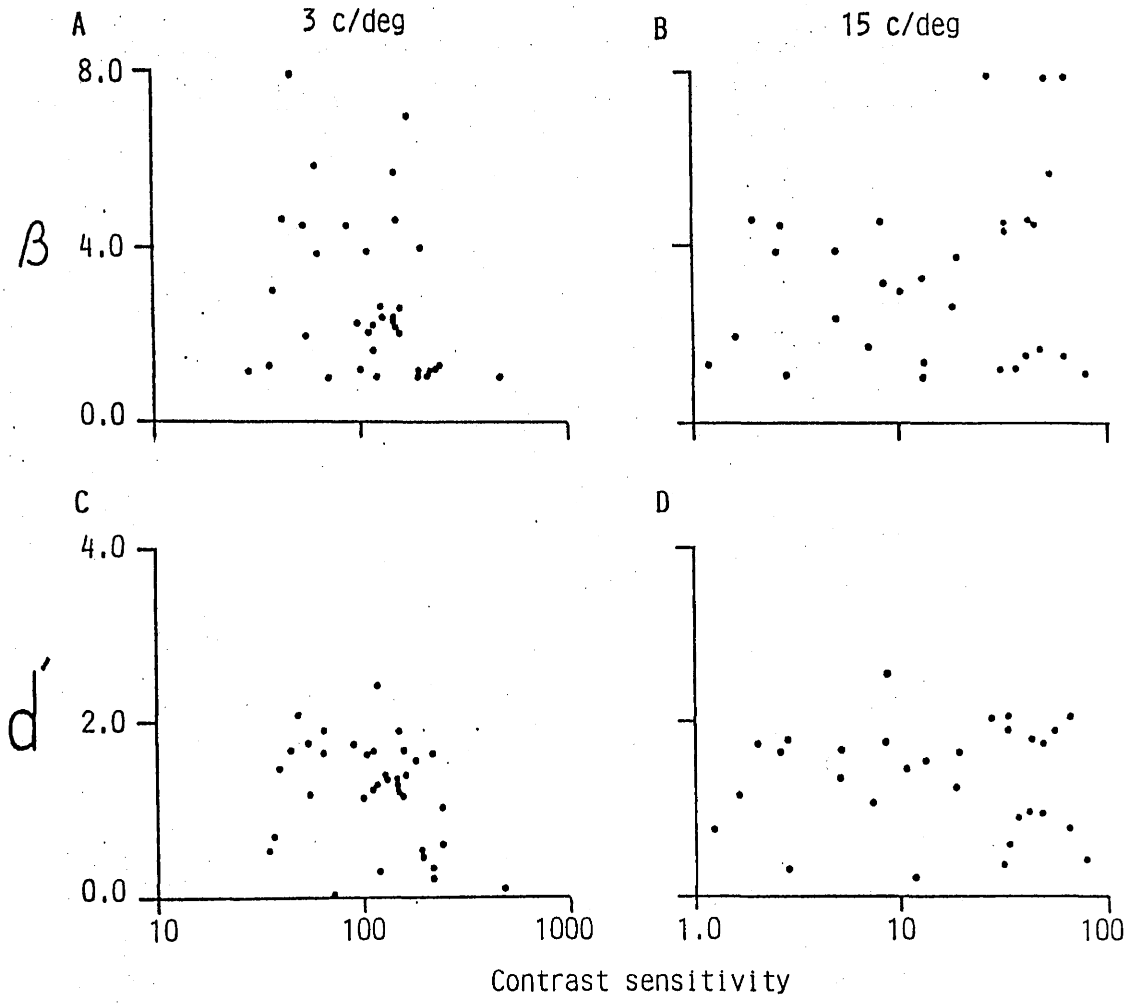


FIGURE 27. Correlation of criterion (β) (A & B) and sensitivity (d′) (C & D) at 50% hit rate against contrast sensitivity (logarithmic units) determined by 50% hits method.

Percentage bias was also statistically examined in this way. At 3 c/deg a linear regression of log contrast sensitivity against percentage bias was found to be non-significant (r=-0.236 for ascending method; r=-0.232 for the 50% hits method) (p>0.1). The same was true for 15 c/deg: no significant correlation was found between log contrast sensitivity (ascending method) and percentage bias (r=-0.132) nor between log contrast sensitivity (50% hits method) and percentage bias (r=0.108) (p>0.5) (Fig. 28).

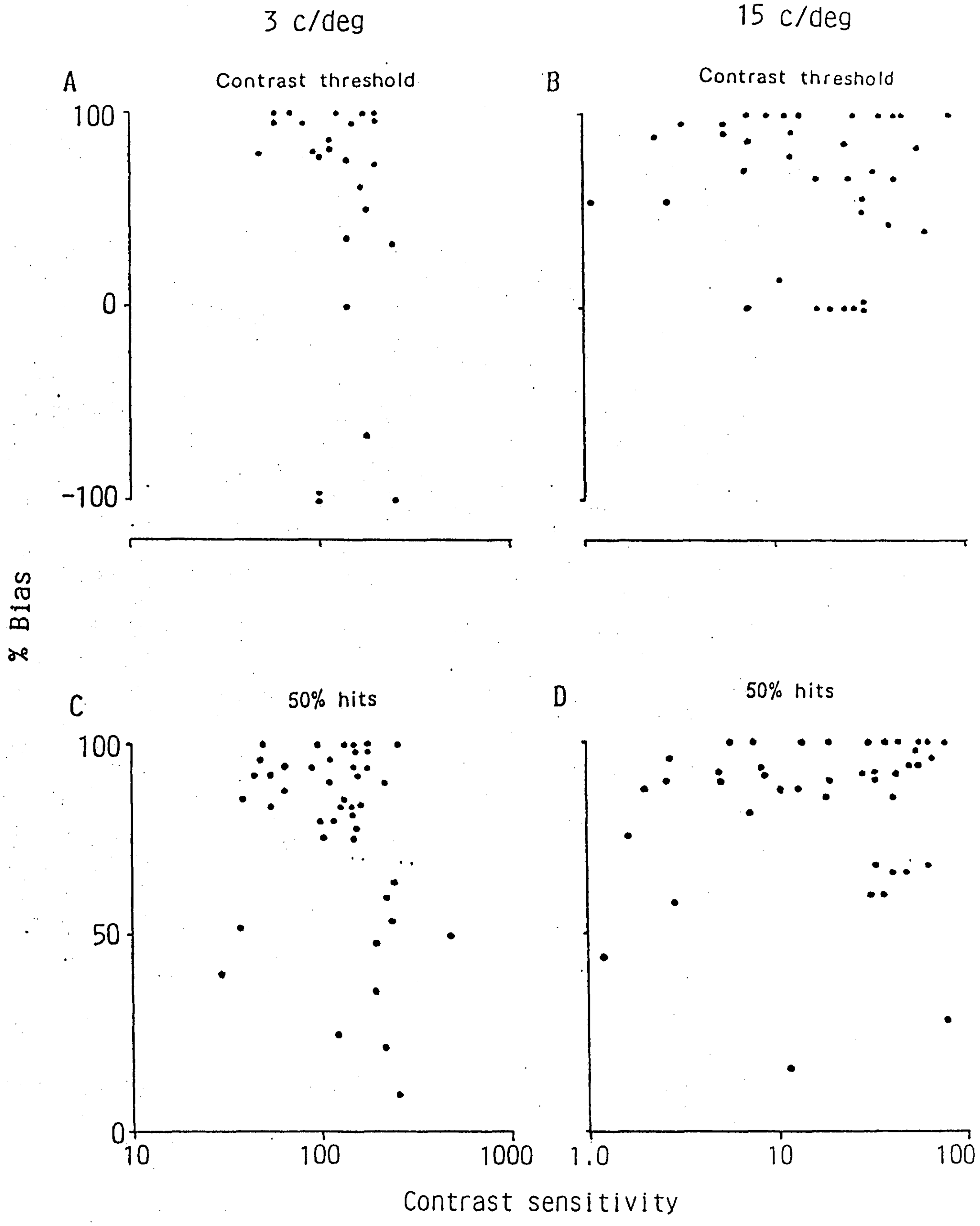


FIGURE 28. Correlation of percentage bias at contrast threshold against contrast sensitivity (ascending method) (A & B) and percentage bias at 50% hits against contrast sensitivity (50% hits method) (C & D).

Bekesy tracking method of decreasing contrast, increasing contrast. Each technique has its advan disadvantages. [illegible] (19..) compared th

DISCUSSION

An ascending method of threshold determination showed that older subjects were less sensitive than young subjects to grating patterns of spatial frequency at the peak of the contrast sensitivity function (3 c/deg) and of a moderately high spatial frequency (15 c/deg). These results were in agreement with the previous studies which had found such a loss occurring with age (see General Introduction). The possibility under consideration here is that this age-related reduction in sensitivity is due to older people being more conservative in their decision-making than younger people. In other words, they may require the grating pattern to be of a higher contrast before they feel able to commit themselves to a decision as to whether the stimulus is present.

Contrast threshold and psychophysical equivalence

Although the main area of interest is that of age and its effect on visual functioning, a side-issue relating to methodology has also been investigated. The determination of contrast sensitivity can be carried out using a variety of techniques: for example, method of limits, method of adjustment, Bekesy tracking, method of decreasing contrast, method of increasing contrast. Each technique has its advantages and disadvantages. Ginsburg and Cannon (1983) compared three of the above methods (Bekesy tracking, method of adjustment, method of increasing contrast) in terms of repeatability, reliability and speed. In all of these aspects the method of increasing contrast (or ascending method) was superior to the other two. The present study also serves to point out the advantageous aspects of the ascending method.

Even discounting the difficulties inherent in the concept of an absolute threshold there are still the problems which arise due to lack of standardisation in both terminology and methodology. Different techniques, as mentioned above, can yield different measures of threshold. Furthermore, one's definition of threshold (in terms of subject performance on a particular task) might also vary and, not surprisingly, yield different results with the possible outcome that straightforward comparisons become problematic. One such definition might be called the 'just-visible-and-no-more' measure of threshold where, irrespective of the method used, the threshold is regarded as the point where the subject is able to see the stimulus but where a further reduction in intensity would make the stimulus imperceptible. Another measure of threshold is dependent on the construction of a 'psychometric function' where the stimulus is presented at a full range of intensities and the percentage detection rate obtained for each level. Having specified such a relationship (in vision, referred to as a 'frequency-of-seeing' curve) threshold can be set at a percentage of correct responses (often 50%) and the stimulus intensity which yielded the chosen detection rate obtained.

Determination of contrast sensitivity using a method which specifies threshold as the contrast at which 50%-of-seeing occurs demands (as did the SDT component of the present study) a relatively large number of trials in order that the 50% level be properly set. Using this approach, a single point on the contrast sensitivity function would require at least half an hour to determine. The full contrast sensitivity function (requiring, at minimum, several points) would need many hours of testing. As Ginsburg and Cannon (1983) pointed out, rapidity is one of the chief advantages of the ascending method. In the present study it was shown that this method not only gives data which is comparable to that of the 50%-of-seeing method but gives it in a fraction of the time (using the ascending method, each point on the CSF would require only a few minutes to determine). This advantage is most important in those instances where subject fatigue or attention span is likely to be an important factor. As Horace Barlow (1977, p347) has pointed out, unless frequency-of-seeing curves are measured with extreme rapidity, there is "...the risk of finding an unresponsive subject asleep on his bite bar."

A second side-issue also addressed by the present work is the validity of using contrast multipliers as psychophysical comparators. There is an assumption that the threshold contrast for each subject, although invariably different in absolute terms from individual to individual, provides a common psychophysical reference point such that, multiplying the obtained measure by a fixed value will give a stimulus of a contrast which, though *physically* different in different people, will be *psychophysically* identical i.e. will look the same irrespective of its value in terms of contrast units. Although there is no way to directly investigate the validity of this assumption the question can be handled by indirect methods. One way would be that of the main topic of the present work: attempting to separate the effects of criterion from the effects of sensitivity. Another way would be to observe the behaviour of subjects on a task different to that which determined their original threshold but which depended on that threshold's validity as a common reference point. If the form of the behaviour appeared similar then this would suggest that equivalent multiples of threshold (or, more precisely, equivalent increments of these threshold multiples) produced equivalent increments of subjective sensation. The present study showed that the 'extremes' of detection performance ('extremes' represented by 25% and 75% hit rate) were separated, in subjects of different ages and hence different thresholds, by a similar number of discrete increments of threshold multiple. In other words, an increase in stimulus contrast from, for instance, 1.4x to 1.6x threshold in an old subject produces an improvement in detection performance equivalent to that produced in a young subject by an increase from 0.6x to 0.8x threshold.

Signal detection

In examining the results of the signal detection experiment, perhaps the most striking aspect is the disparity in results between the higher and lower spatial frequency.

15 c/deg

In summarising the results at this spatial frequency the main finding is the general lack of significant difference between young and old subjects. Sensitivity showed no significant variation with age at each of the three multiples of contrast threshold which were tested (0.8x, 1.0x and 1.2x). These results are thus consonant with the fact that the original threshold determination using the ascending method was an adequate and valid point of common reference for subjects of all ages and that the multiples of threshold above and below this point are equally valid as alternative comparators. When the comparison is made at the 50% hit rate, again there were no significant age effects apparent.

Criterion at 15 c/deg did not change significantly with age whether calculated at 0.8x, 1.0x or 1.2x contrast threshold or derived from the 50% hit rate. Percentage bias also did not change significantly with age except in a single instance, at 1.0x contrast threshold, where it was higher in old than in young. However, the difference was not present when the comparison was made between the young and the very old groups.

3 c/deg

As was the case for the higher spatial frequency, there was for 3 c/deg a lack of significant difference in the sensitivity of young and old subjects at contrast threshold itself and at the higher and lower multiples of this threshold. At the 50% hit rate both of the older groups had significantly higher mean values of d′ (greater sensitivity) than the young group.

Criterion was unaffected by age when compared at the three multiples of contrast threshold. However, at 50% hits both older groups had a significantly higher β than the young group indicating that the latter were less conservative in their decision-making. Somewhat paradoxically, when percentage bias was compared across the three age groups there were no significant differences at the 50% hit rate. On the other hand, a significant increase was observed in the older groups at all three multiples of contrast threshold although not in the very old group at 1.2x threshold.

The possibility that age-related effects were present but that criterion was related to contrast sensitivity (the latter reduced with age) rather than to chronological age *per se* was explored by attempting to correlate β with contrast sensitivity. The lack of correlation indicates that an age-related trend was not obscured by the inherent scatter of the contrast sensitivity data. Percentage bias was also found to be uncorrelated with contrast sensitivity.

At contrast threshold (i.e. using a stimulus which is of a contrast 100% that of the threshold value obtained using the ascending method) there was no significant difference between young and old observers in terms of both d′ and β. However, a possible objection is that the lack of differences between the groups is due to the fact that the younger members of the older group (i.e. those in their 50s or 60s) were performing in a manner which might have been more representative of young observers; this would unduly bias the overall performance of the older group, perhaps disguising genuine age effects. To circumvent this objection a comparison was made with the old group restricted to those subjects who were aged 70 yrs or over. Where significant differences had previously been found, these were maintained; at 50% hits, d′ and β were higher in older subjects.

The '50% hits' measure provides an alternative index of comparison to those made with specific reference to the pre-determined contrast threshold. In order to accommodate individual differences in performance the range of grating contrasts presented to each subject was variable and it was often the case that the stimulus of 1.0x contrast threshold was of a value outwith this range (i.e. was either too high and hence yielded a 100% successful detection rate, or was too low and gave a 0% detection rate). An advantage of a comparison at the 50% hit rate is that, except in those instances where no false alarms were made, d′ and β could be calculated for all subjects. Since at 3 c/deg the contrast at which the 50% hit rate occurred was significantly higher than contrast threshold in the older subjects but not in the young subjects, this would suggest that this method of comparison reveals a greater difference in sensitivity between the two groups than does the ascending method. In other words, at 3 c/deg the ascending method actually underestimates the sensitivity difference between young and old subjects. This becomes more apparent if the stimulus contrast which produced a 50% hit rate is converted into a measure of sensitivity. For the younger subjects the log contrast sensitivity obtained by this method is no different from that obtained by the ascending method; for the older observers, however, the '50% hits' log contrast sensitivity is significantly lower than that obtained by the ascending method (Fig. 15). Hence, the difference between the two groups is accentuated at the 50% hits level. At this level of pattern detection it would appear that at least one of the two groups is employing a different perceptual/decisional strategy or is operating under different perceptual constraints to those applying in the determination of contrast threshold by the ascending method. (In order to avoid constant qualification, this and subsequent discussion will always be with reference to 3 c/deg unless otherwise stated).

The problem would appear to be why the older people should have exhibited such a disparity between performance on the detection task and on the threshold determination task. It may be that, in the latter case, the younger subjects, while in absolute terms requiring less stimulus contrast to see a grating pattern than do older subjects, were in relative terms using more contrast than they actually required. This might suggest that the younger people were more conservative than older people in determining threshold. The 'extra' contrast which they allowed themselves was perhaps sufficient to accommodate the different (and possibly more rigorous) demands of the signal detection task. Older people, having more precisely specified their threshold, are less equipped to cope with the detection task and hence require more contrast, relative to their own threshold, than do younger subjects. However, this seems unlikely given the fact that in no instance was the young group found to have a higher β or percentage bias than the old group (which would have indicated a more conservative decision-making) and given also that the young group's mean contrast sensitivity is the same for both methods of threshold determination.

However, other explanations are possible. One can instead start from the not unreasonable assumption that the two tasks do indeed have different demand characteristics. Examination of the requirements each place on the subject makes it difficult to decide which of the two is perceptually more taxing. Following the experiment, several of the subjects were informally questioned (in some cases spontaneously volunteering the information) as to which of the two threshold-determining paradigms they had found to be most demanding; answers were mixed: those who considered the detection task to be 'harder' generally reported that this was due to the paced nature of the experiment (i.e. that they were working, in a sense, 'against the clock'); those who considered the detection task to be the 'easier' of the two often commented on the fact that the 'flashed' presentation made the target easier to spot (one subject pointed out that he had two chances for detection - "..when [the pattern] comes on and when it goes off again"). It is apparent that, intuitively, it is difficult to rate the tasks in terms of difficulty. However, for the purposes of the discussion, if one regards (as many of the subjects did) the detection task as being the more demanding of the two then how does this help to explain the observed results? In the experimental protocol which was used, subjects first specify their threshold using the ascending method. When they are then faced with the detection task it may be the case that young subjects find it less demanding than do the elderly observers. One consequence of this would be that the threshold contrast which they had previously set themselves would be adequate to cope with the new impositions of the detection protocol. In other words, the threshold obtained using the ascending method would appear to accurately reflect that obtained using the 50%-hits method. Older people, faced with a detection task which they might consider to be more demanding than do young subjects, will find that their previously set threshold (although perhaps no less 'accurate' than that of the young) is inadequate for the detection task ('inadequate' in the sense that the range of contrast multipliers over which 0-100% detection occurs is higher - relative to the original threshold - than that of the young subjects).

For the determination of threshold using the signal detection protocol, the nature of the technique demands that the subject should only see the stimulus 50% of the time. In this respect, one would expect the threshold from the detection task to be lower than that from the ascending task (where threshold is more akin to 100% of seeing). In fact, since for young people the two values were virtually identical while for old people the detection threshold was actually significantly higher, this suggests that, for older people, detection is indeed the more demanding of the two tasks. This would appear to be borne out by the fact that, in older people, the log contrast sensitivity obtained with the ascending method was significantly higher than that for the 50% hits method.

Signal detection and spatial frequency

One is led to ask the question: why is stimulus detection at 3 c/deg more demanding for old than young? A possibility is the afore-mentioned 'paced' nature of the task and the fact that the stimulus is only presented for a relatively short period of time; perhaps a stimulus of longer duration would be easier to detect, negating the differences which were observed between young and old. However, this would appear to be an unlikely explanation. Eriksen and Steffy (1964) found that old subjects could attain the same level of performance (detection of Landolt C orientation) with exposure durations of 300 to 500 msec as that achieved by young subjects with shorter stimulus durations. Since, in the present study, the stimulus is presented for 500 msec, it seems unlikely that the duration was so short as to compromise the performance of the elderly subjects relative to that of young.

In fact, since the above discussion pertains to the differences between subjects occurring with the use of a 3 c/deg stimulus, the question arises as to why these differences are not present when a 15 c/deg stimulus is used. At the higher spatial frequency the multiple of contrast threshold which produced 50% hits is not significantly different between groups. At the lower spatial frequency, on the other hand, old people perform worse than young people, requiring more contrast, relative to their own contrast threshold, in order to achieve a 50% hit rate. The characteristics of the 3 c/deg stimulus must impose on the observer perceptual demands with which the old subject is less able to cope. At 15 c/deg there are no significant differences between old and young people, therefore the characteristics of the stimulus must impose similar demands on each age group.

Tolhurst (1973) suggested that, with respect to the processing of spatial information, the visual system could be regarded as consisting of two different types of channels. At low spatial frequencies (below 4 c/deg) the channels which predominate are highly sensitive to patterns which are temporally modulated; at higher spatial frequencies sensitivity is relatively unaffected by temporal modulation of the stimulus.

Breitmeyer and Julesz (1975) found that, at low spatial frequencies (below 5c/deg), a feature important to detectability is pattern onset; a stimulus which is abruptly presented is more easily detected (will have a lower threshold) than a stimulus which is gradually presented. In other words, contrast sensitivity to low spatial frequencies is increased when the stimulus contains temporal transients. At high spatial frequencies, on the other hand, abrupt presentation has no influence on sensitivity. In a reaction time study, Tolhurst (1975) showed that, using a low spatial frequency pattern, reaction times were grouped after stimulus onset or offset (i.e at transients) whereas, using high spatial frequencies, reaction times were distributed throughout the duration of the stimulus presentation.

Since at 3 c/deg transient channels are in operation, while at 15c/deg sustained channels dominate (Kulikowski and Tolhurst, 1973), it appears in the present study that the transient channels are more strongly affected by age. There is evidence to suggest that the senescent visual system is indeed characterised by a reduction in temporal resolving power. For example, the critical flicker fusion frequency (CFFF) - the minimum number of light / dark alternations per second at which an observer perceives an intermittent light as being steady - has been shown to be age-dependent (although involving luminance channels rather than the transient system outlined above). Brozek and Keys (1945), testing female subjects between the ages of 18 to 60 years, found that the CFFF was significantly lower above the age of 45 years, i.e in these older individuals there was an impairment in the ability to see a flickering target. Sensitivity to flicker was also shown to vary with age by Wright and Drasdo (1985); three temporal frequencies were tested: 3.3, 10 and 30 Hz. For the two lower frequencies, there was a progressive decrease in sensitivity above the age of 40 yrs. For the 30 Hz frequency, sensitivity was progressively reduced above the age of 20 yrs.

Older subjects have also been found to have a lower dynamic visual acuity than young subjects; when the stimulus used is a moving target then the progressive decline in acuity with age is more pronounced than that seen with a stationary target (Burg, 1966).

Movement of a grating pattern is known to enhance contrast sensitivity to low spatial frequencies i.e. the threshold to a temporally modulated pattern will be lower than that of a stationary pattern (Robson, 1966). Although this is true for subjects of all ages, Owsley, Sekuler and Siemsen (1983) found that the enhancing effect of motion on sensitivity was age-dependent. A phase-reversed 1 c/deg grating pattern was found to have a lower detection threshold than a similar but stationary grating. The amount of enhancement, however, was found to decline with age (age range tested was 19 - 87 years).

Although the above studies provide evidence for an age-related transient system impairment, there is a slight problem with this interpretation of the present results which can be expressed as follows: if the difference at 3 c/deg is due to a differential decline in the transient system with age, and if a briefly-presented stimulus is held to enhance contrast sensitivity, then why is the young observers contrast sensitivity as determined by the 50% hit rate method no different from the contrast sensitivity determined by the ascending method? If, in the former case, the stimulus is one which is mediated by the transient system then one might expect the motion-enhancement effect to produce a higher contrast sensitivity when the on-off presentation of the detection paradigm is used. This apparent anomaly can perhaps be explained in terms of, as mentioned before, the fact that the two tasks have different characteristics. Perhaps performance on the detection paradigm is a compromise between the enhancement due to the transient nature of the stimulus and a detriment due to some other unrelated aspect of the task (for example, the paced nature of the experiment or the greater concentration required). If, in young people, the motion-enhancement effect is just enough to compensate for the extra demands of the signal detection task, then the enhancement in old people (reduced with respect to that of young) might <u>not</u> be sufficient to overcome these extra demands; hence, the fact that young people have similar contrast sensitivities using both methods could be due to a trade-off between facilitatory and disadvantageous aspects of the detection protocol. However, if such an explanation pertains then one would expect that at 15 c/deg, where no transient cues are present, young people would fare worse on the supposedly more demanding detection task than on the ascending method task. In fact, at this higher spatial frequency there were no significant differences. It may be the case then, that little or no enhancement occurs when the briefly-presented stimulus is used but that a decline in the transient system in old people simply means that they are less able to process the brief stimulus and are handicapped accordingly.

Decision-making and ageing

For 3 c/deg at contrast threshold (and, generally speaking, at 0.8x and 1.2x threshold), the fact that percentage bias is significantly higher in older people suggests that they are more conservative in their decision-making than the young group. If one compares hit and false alarm rates in young and old subjects then it becomes apparent why this should appear to be the case: with a stimulus at contrast threshold young people responded 80% of the time (combined hit and false alarm rate of 0.68 and 0.12 respectively); old people responded only 52% of the time (combined hit rate and false alarm rate of 0.47 and 0.05 respectively). Hence, for the same stimulus, old people were less likely to make any kind of response than were the young people. This finding is in keeping with those of Silverman (1963) where, in a task involving identification of tachistoscopically-presented words, older subjects gave fewer voluntary responses relative to their forced-choice responding than did young subjects. In addition to the above, in the present study the proportion of those responses which were inappropriate (i.e. false alarms) was 14% in young compared with only 10% in old, a finding which is again suggestive of greater conservatism in the older subjects.

Although the significant differences in percentage bias would seem to be indicative of differences in criterion between young and old it would be premature to draw such firm conclusions. Earlier, it was pointed out that at 3 c/deg old people appeared to find it more difficult to detect the pattern due to its transient presentation. If one accepts this suggestion then one is faced with the question as to whether it is strictly valid to make any comparisons in terms of performance on the two types of task (ascending method and signal detection). Any conclusions concerning criterion differences would have to bear in mind the fact that, although the stimuli were made psychophysically equivalent relative to threshold determined by the ascending method, at 3 c/deg there is the additional confounding factor (unrelated to decision-making) of the transient system decline in old people.

Using the ascending method, the common point of reference is the contrast threshold. At 3 c/deg, due to the differential sensitivity of the transient system in young and old, this point of comparison no longer becomes wholly valid. In other words, cross-task comparisons (i.e. at contrast threshold or multiples thereof) are made difficult due to the different demands of the two tasks and due to the way in which age interacts with these demands.

At 15 c/deg, age-related differences in transient system sensitivity should not intrude on the comparison between young and old subjects. In fact, at this spatial frequency, both methods of determining response bias (criterion β and percentage bias) failed to show any significant effects with age.

At the lower spatial frequency, the significant age-related differences in percentage bias are possibly solely due to the nature of the detection task itself. At contrast threshold the pattern which is to be detected is less easily seen by the older person (as indicated by the greater contrast required in order to achieve the same hit rate as a young person). It may be the case that a stricter criterion comes into operation when the stimulus is one which is difficult to detect. In fact, criterion β for all subjects showed no significant variation with contrast when normalised with respect to the 50% hits measure (Fig. 19). However, if one looks at the mean magnitudes of both β and percentage bias and how they vary according to multiple of contrast threshold (Tables 2 and 3) it is apparent that there is a general trend towards a reduction in value for both variables with increasing contrast i.e. subjects (whether young, old or very old) tend to be somewhat more conservative at low contrasts. Given this, it appears more likely that the reason why percentage bias is significantly higher in old than in young, when compared with respect to contrast threshold, is due to the manner in which bias is related to contrast rather than to effects of ageing *per se*. There is also the possibility, expressed by Watson et al (1979), that age-related criterion differences only arise when a sensory impairment already exists. Reduced sensitivity to transiently presented stimuli might result in a reluctance to ackowledge the presence of a degraded signal - hence the greater apparent conservatism.

A further reason to be cautious in accepting the significant differences in percentage bias at face value is the fact that bias was found to be uncorrelated with log contrast sensitivity. This would appear to be difficult to reconcile with the fact that bias was shown to be age-dependent (given that contrast sensitivity is also age-dependent). One might have expected a lower contrast sensitivity to be associated with a stricter criterion. However, this finding does not necessarily invalidate the argument that ageing is associated with a stricter criterion; the amount of scatter in the log contrast sensitivity data (Fig. 10) means that in both age groups there will be a considerable range of contrast sensitivities. Since the core of the argument is that the decision-making of young people is different from that of old people then the fact that some young people have a relatively low contrast sensitivity (possibly falling within what might be considered the 'old' range) would not necessarily be due to the same reasons as those which cause the reduced sensitivity in old people. If a significant relationship had been found then this might have suggested that all differences in contrast sensitivity were due to criterion differences. Hence, although the lack of correlation between bias and contrast sensitivity throws further doubt on the age-related trend towards greater conservatism, it would not in itself be sufficient reason for rejecting the findings.

For 3 c/deg, at the 50% hits measure, the older subjects were more sensitive (higher d') than the young subjects and, moreover, were employing a stricter criterion (as indicated by the significantly higher values of β). The question arises as to why this should be the case at this point of comparison and not at contrast threshold where both d' and β showed no significant changes with age. An obvious reason for the greater sensitivity in the older subjects would appear to be the fact that the contrast which, for them, yielded a 50% hit rate was greater (relative to their pre-determined contrast threshold) than that of young subjects. Since the contrast was higher (both relatively and absolutely) it is perhaps not surprising that the older groups should appear more sensitive. However, this explanation is somewhat unsatisfactory. One point made earlier was that over the range of contrasts which gave the full range of detection rates, the performance of young and old persons was comparable in that the psychometric function was similar both in form and magnitude (i.e. same shape and extending over a similar percentage of contrast change). Having emphasised the comparability of stimuli and response when 'normalized' with respect to the 50% hit rate, it seems unreasonable to invoke an apparent psychophysical difference at the 50% hit rate to account for the difference in sensitivity. Closer inspection of the data reveals a more apposite explanation. Since at 50% hits the hit rate is, by definition, invariant, the differences in sensitivity between young and old must be due to differences in false alarm rate. If one compares false alarm rates at the 50% hit rate (ignoring zero false alarm rates which do not contribute in the calculation of d′) then one finds that the young subjects make significantly more false alarms than do the old subjects. If two observers attain the same hit rate then the one who makes fewer false alarms would be considered to be the more sensitive of the two (basically because fewer of his or her 'correct' responses could be regarded as lucky guesses). Hence, it might be said that the apparently higher sensitivity of old people at 50% hits is a spurious result. If one compares false alarm rates of young and old subjects at the 50% hit rate but this time including zero false alarm rates then there is <u>no</u> significant difference between age groups - this can only be due to the fact that the young group contains a greater proportion of people who make no false alarms at the 50% hit rate. One cannot conclude that this means that the young group is necessarily <u>more</u> sensitive than the older group but it does render suspect (and, in a sense, artefactual) the differences in d′ at this level of comparison.

The same is largely true for criterion β and also serves to explain another apparently anomalous result. Both β and percentage bias are measures of the subject's criterion; higher values of either are indicative of more conservative decision-making. However, the two methods yielded what are seemingly contradictory findings. At the 50% hit rate, β is significantly higher in old than in young; percentage bias, on the other hand, showed no significant difference when the comparison between groups was made at the 50% hit rate.

As was true for d′ at 50% hits, the same applies to β: in calculating the latter, no zero false alarm rates are included; since older groups have, in these circumstances, a lower false alarm rate than young then this serves to explain why they appear to be more conservative - a lower false alarm rate for an identical hit rate would suggest a stricter criterion - less apt to report 'noise-induced' sensation as being due to the stimulus. If the zero false alarm rates are included in the determination of the subject's criterion (as they are in the calculation of percentage bias) then the difference which was originally observed (in terms of β) becomes non-significant.

In summary, the age-related increase in percentage bias at 3 c/deg contrast threshold seems more likely to be due to the different demands which the detection task makes on old people. At the very least, one cannot conclude that these task-related factors do not contribute in some way to the different response behaviour in the elderly. The differences in β at 3 c/deg 50% hits are equivocal due to the fact that a larger proportion of young than old made no false alarms and are hence excluded from the analysis. (This also points out the advantage which the calculation of percentage bias has over criterion β in such instances).

At 15 c/deg, the results are much less likely to be influenced by the possible confounding effects of an age-related transient system deterioration. One can feel more secure about accepting as genuine the general lack of signicant criterion differences.

If one looks at the grouped data (mean β and median percentage bias; Tables 2 and 3) it is clear that at both spatial frequencies and in almost all cases (at the various multiples of contrast threshold and at 50% hits) the magnitudes of both measures of response bias are greater in the older groups than in the young group. Bearing in mind the above-mentioned qualifications as regarding those instances where the differences <u>were</u> significant, one can conclude that older people <u>are</u> somewhat more conservative in their decision-making than are young people but not to any significant extent. In this respect, the differences in criterion are unlikely to contribute substantially to the observed differences in visual performance. The cause of the loss in contrast sensitivity must therefore lie in the visual pathway at a level prior to that at which decision-making occurs.

INTRODUCTION: The visually evoked response

The *electroencephalogram* or EEG is a record of the ongoing electrical activity of the brain. While it has proved possible to relate changes in this activity with particular states of consciousness (or perhaps, more correctly, states of arousal) there has been disappointingly little progress in correlating electrical status with psychological status since the early days of the technique's development. A more fruitful method of investigating the relationship between electrophysiological function and psychological or perceptual factors is by means of the *averaged evoked response.*

On presentation of a stimulus there is a change in the EEG, the extent and nature of which will depend on the modality and the site of recording. This electrical response is generally so small as to be buried within the non-specific background activity. However, if the stimulus is presented a number of times and the responses averaged, the 'random' activity ('random' in the sense that it is not time-locked to stimulus presentation) should cancel out while the response, if itself time-locked, should be boosted. In such an averaging procedure, the signal-noise ratio is proportional to the square root of the number of repetitions. Early techniques relied on photographic superimposition (Dawson, 1947) in which individual waveforms were overlaid, the response elicited by the stimulus becoming apparent as the more dense areas of the superimposed traces. An obvious problem with this method was that due to the high amount of noise it was often difficult to accurately discern the waveform within the background activity. As an improvement, Dawson (1951) developed the technique of summation whereby the individual records were added and the mean response obtained (although perhaps Dr J. N. Hunt should be rescued from the small print of scientific history since, in a footnote to the paper, Dawson credits him with the original idea). Dawson also introduced the first automated averaging system, a mechanical device involving addition by a bank of condensors. Research in this area has, perhaps more than most, been tied to innovation in equipment and technology. Recent developments in computer science now mean that averaging can be carried out far more quickly and with more accuracy than had previously been possible.

THE VISUALLY EVOKED RESPONSE

Using visual stimulation, the response thus evoked is termed, not surprisingly, the *visually evoked response* (VER). On the basis of the temporal frequency of stimulation (and, accordingly, the characteristics of the response) the VER can fall into two descriptive categories known as the *transient VER* and the *sustained VER*. In the former case, the stimulus is repeated at a frequency sufficiently low as to allow the visual system to return to its 'resting' state between presentations. In these instances the response obtained can be divided into different sub-components, usually labelled according to their polarity and their latency-to-peak or numbered sequentially according to their appearance in time; hence a waveform component could be designated as N1, the first negative component after stimulus onset, or as N100, the negative component peaking at 100 msec after stimulus onset. Analysis of this type of VER usually takes the form of latency and amplitude measurements.

In the case of the sustained VER, the stimulus repetition rate is so high (typically 8Hz or over) that the system has no time to 'recover' between the successive stimulus presentations. The waveform is no longer resolvable into its constituent components and takes the form of a sinusoidal wave, the fundamental frequency of which will be the same as the temporal frequency of stimulation. Analysis is concerned primarily with the frequency characteristics, the phase shift, and the amplitude of the response.

The complexity of the stimulus is another determinant of the form of the VER and its resulting classification. At the most basic there are two types of visual stimulus: pattern and luminance. The latter term applies to a flash stimulus where the stimulation arises purely due to changes in luminance; the former term refers to those situations where a spatially-structured stimulus is used. This can, of course, apply to a wide variety of stimulus types, ranging from lines and edges to numerals, letters and even words. Perhaps the most widely used form of patterned stimulus is the checkerboard pattern. Three modes of presentation have commonly been employed. The first of these is checkerboard flash where the array of alternating black and white squares is illuminated by brief flashes of light. The problem with this type of presentation is that the response will contain components which have been elicited by luminance changes as well as pattern-specific components - once so confounded it is difficult to separate the two responses.

The other two forms of presentation can be termed 'reversal' (where the checks alternate from black to white and back again, the overall luminance of the display staying constant) and 'onset' (where the pattern replaces a uniform field of the same mean luminance). In both of these instances the waveform obtained is elicited due to the patterned elements of the display and should be uncontaminated by luminance changes.

The latter two types of presentation can also be used for another form of patterned stimulus - the sinusoidal grating pattern.

THE VER TO A GRATING PATTERN STIMULUS

This type of transient response generally contains two prominent positive components, each preceded by a negative component and typically labelled with the notation shown in Figure 29 (e.g. Parker and Salzen, 1977a; Reed, Marx and May, 1984).

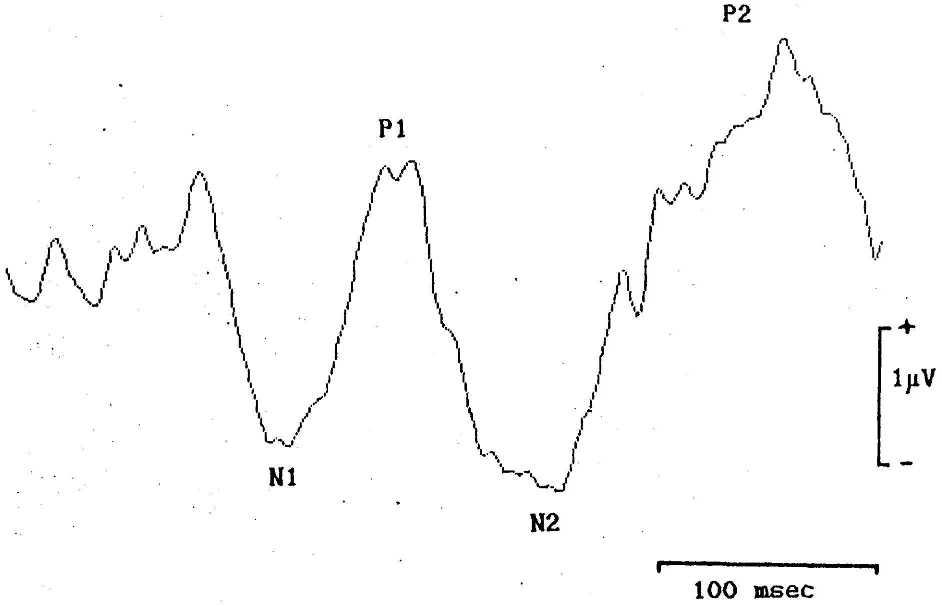


Figure 29. Typical PVER to a grating pattern stimulus.

The latency of these waves is dependent on stimulus features. The two main characteristics of a sinusoidal grating pattern are its contrast and spatial frequency; alterations in either will affect the visually evoked response.

Parker and Salzen (1977a and b) and Parker, Salzen and Lishman (1982b) found that increasing the spatial frequency of a grating stimulus resulted in an increase in the latency of the components of the transient pattern visually evoked response (PVER), an effect that was more pronounced in the earlier components (those appearing before 180 msec) than in the later components (appearing after 180 msec). Plant, Zimmern and Durden (1983) showed that the shape of the latency vs spatial frequency curve was the inverse of the shape of the contrast sensitivity function i.e. latency was at a minimum with a stimulus spatial frequency of 2 c/deg and was more prolonged with lower and higher spatial frequency stimuli.

One problem with these particular studies is that the physical contrast was kept constant throughout the range of spatial frequencies used. As perceived contrast varies with spatial frequency then the results obtained might well have been due to the changes in perceived contrast rather than to any spatial frequency-dependent effects. One way to surmount this problem is to make equivalent the apparent contrast at each spatial frequency by presenting each stimulus at the same suprathreshold level. For example, Vassilev and Strashimirov (1979) presented grating patterns which were five times greater than threshold at each spatial frequency used (1-15 c/deg). Even with psychophysically equivalent contrasts there was still an increase in evoked potential component latency with increasing spatial frequency. Reed et al (1984), using contrasts which were a fixed percentage above threshold, found a curvilinear relationship between latency and spatial frequency. The latencies of both N1 and N2 decreased when spatial frequency was increased from 0.5 to 2 c/deg, and increased when spatial frequency was raised above 2 c/deg.

Amplitude of the evoked response is also affected by stimulus parameters. Reed et al (1984) found that the amplitude of separate VER components was affected to a different extent by varying the stimulus spatial frequency; the amplitude of the P1 component peaked at 4 c/deg while that of the P2 component peaked, less sharply, at 1-2 c/deg. Similar results were obtained by Plant et al (1983) although the amplitude of N1 and P1 was greatest at *ca* 8 c/deg. Parker and Salzen (1977a) also observed maximal P1 amplitude between 4-8 c/deg. However, unlike Reed et al (1984), they found that P2 amplitude peaked at higher spatial frequencies. Jones and Keck (1978) showed that, at spatial frequencies between 0.5 to 10 c/deg, reducing the contrast of the grating stimulus caused a reduction in the amplitude and an increase in the latency of N1. At contrasts higher than 0.25, saturation of the response was observed. The behaviour of other VER components was not as consistent as that of N1. A similar contrast-dependent effect on P1 amplitude was noted by Parker et al (1982b) with the difference that the contrast vs amplitude function was 'two-branched'; above 10% contrast any further increase in contrast had a proportionately greater effect on amplitude than a similar increase below this contrast value.

The nature of the relationship between stimulus contrast and response amplitude was investigated by Campbell and Maffei (1970) and Campbell and Kulikowski (1972). Using stimulation of a relatively high temporal frequency (appearance / disappearance or pattern reversal of a grating pattern at a rate of 8Hz), they showed that the amplitude of the potential varied with the logarithm of the contrast of the grating pattern. However, at near-threshold presentations the relationship became linear. They also found that the contrast at which the VER reached the theoretical zero voltage (determined by extrapolation of the suprathreshold results) was very close to the psychophysical contrast threshold. Furthermore, the waveform evoked when the subject reports detecting a near-threshold grating stimulus shows no correlation with that observed when no detection has occurred. However, it correlates highly with the waveform seen when the subject is uncertain about whether or not he or she had perceived the stimulus (and presumedly had experienced something to engender this uncertainty) (Campbell and Kulikowski, 1971).

A number of other studies have demonstrated a similar relationship between psychophysical and electrophysiological thresholds (e.g. Bodis-Wollner 1976, 1977; Harris, Atkinson and Braddick, 1976; Pirchio, Spinelli, Fiorentini and Maffei, 1978).

PHYSIOLOGICAL ORIGIN OF PVER

The components of the PVER have been shown to vary with the retinal location of the stimulus. When the lower retina is stimulated with a repetitive pattern of isolated unfilled squares, negative peaks at *ca* 80 msec and 180 msec and a positive peak at *ca* 110 msec are observed; when the upper retina is stimulated the polarity of the peaks is reversed (Jeffreys, 1971). On the basis of the known retinotopic organization of the occipital cortex, Jeffreys and Axford (1972a and b) proposed that the early component (which they labelled CI) originated in the striate cortex while the second component of opposite polarity (CII) was of extrastriate origin. Lesèvre and Joseph (1980), on the other hand, concluded that only N60 (a component not identified by Jeffreys and Axford (1972a and b)) arose from striate cortex (area 17) and that a more likely origin of P90 (synonymous with CI) was from area 19. Later components N140 and P200 were held to arise from area 18. However, Butler, Georgiou, Glass, Hancox, Hopper and Smith (1987) showed that, when the PVER was recorded at a number of sites, the pattern of voltage distribution of the CI component could best be accounted for by a source in the striate cortex but was not compatible with generation in extrastriate areas. All three components have been shown to occur with pattern onset while only CI is evoked by pattern offset. In addition, the two later components, CII and CIII, are highly sensitive to adaptation and to the presence of contours, unlike CI which is resistant to adaptation and sensitive to contrast, further suggesting that the early and late components are of different origin (James and Jeffreys, 1975).

Using checkerboard reversal presented in different octants of the visual field, Halliday and Michael (1970) observed a similar polarity reversal in the prominent component at *ca* 100 msec when upper and lower field octants were stimulated although only with stimulation of the octants next to the vertical meridian. However, these authors argued that the PVER components all arose from extrastriate areas. In fact, direct comparisons of the data of Jeffreys with that of Halliday and Michael is problematic since there were important differences in the type of pattern used (hollow squares and conventional checkerboard, respectively), the mode of presenation (onset and reversal), and the method of analysis (amplitude measured from baseline and peak-to-peak). However, Estévez and Spekreijse (1974) recorded PVERs to both checkerboard onset and offset and to checkerboard reversal and, by a gradual transition between the two types of stimulation, showed that the components of the pattern reversal VER were essentially the same as the pattern *offset* VER.

Difficulties in comparison arise when sinusoidal grating patterns are the chosen stimulus. Smith and Jeffreys (1978) regarded P1 of the grating PVER as corresponding to CI of the checkerboard reversal PVER. Although a straightforward correspondence between the various peaks of the different PVERs may not be possible, there are a number of similarities. Parker, Salzen and Lishman (1982a) have observed that the first prominent component of the grating PVER exhibits the same polarity reversal when upper and lower fields are stimulated as does component CI of the checkerboard PVER (Jeffreys, 1971). The early and late components of both types of PVER appear to be affected differently by adaptation: early components are little affected whereas later components are greatly reduced after preadaptation (Kulikowski, 1972; James and Jeffreys, 1975).

EFFECTS OF AGEING ON THE VER

Research into the effects of ageing on the visually evoked response has produced varying results. Previous studies in this area have used as stimulus either an unpatterned flash or, more commonly, checkerboard pattern reversal.

Flash VER

Examining those components of the flash VER arriving before 170 msec, Straumanis, Shagass and Schwartz (1965) found a general prolongation of latency with increasing age; the young group ranged in age from 19 to 45 years, the old group from 63 to 86 years. Dustman and Beck (1966, 1969) found that in response to a flash stimulus, the earlier components of the VER (100 msec or less) arrived consistently later in older subjects (mean age 67 years). These findings were replicated by Dustman, Schenkenberg, Lewis and Beck (1977) while similar results were obtained by Buchsbaum, Henkin and Christiansen (1974), who measured an increase in latency of the flash VER components P100-N140 and N140-P200 above teenage years and up to the age of 60. Man'kovskii, Belonog and Gorbach (1978) also found that advancing age was accompanied by a progressive increase in the latency of the flash VER (18-81 years; above 90 years of age the latency was shorter than that found in the 75-89 year group). Cosi, Vitelli, Gozzoli, Corona, Ceroni and Callieco (1982) similarly demonstrated longer latency responses in old subjects (41-80 years) as compared with younger subjects (19-40 years). On the other hand, Wright, Williams, Drasdo and Harding (1985) found that only the P2 component of the flash VER was significantly affected by age.

The amplitude of the flash evoked response has also been reported to be affected by increasing age. Copenhaver and Perry (1964) measured the area beneath the response peak and above the baseline (a measure which correlated highly with amplitude) and found that the size of the response was reduced with increasing age (between 4 and 78 years). The same was true for Buchsbaum et al (1974) who found that not only did older subjects have a smaller amplitude VER but that the amplitude was less affected by changes in flash intensity than that of young subjects.

A number of other studies have reported an *increased* VER amplitude with a flash stimulus, the changes generally restricted to early components, i.e. those arriving before 100 msec (Straumanis, 1965; Dustman and Beck, 1966, 1969; Dustman et al, 1977; Cosi et al, 1982). In the study by Man'kovskii et al (1978), while early components (<120 msec) had a greater amplitude in old subjects, the later components (>190 msec) were reduced in amplitude with age. LaMarche, Dobson, Cohn and Dustman (1986) found no amplitude changes with age. A few studies have used a checkerboard flash as the stimulus. Presenting the pattern at fixed increments above threshold, Dustman and Snyder (1981) and Dustman, Shearer and Snyder (1982) found that the latencies of the VER components labelled N90, P110, N150 and P200 were *reduced* with age although this was attributed to the long latencies in children (age range tested was 4 to 90 years).

Dustman and Snyder (1981) found that amplitudes were largest at the extremes of the age range tested (4 to 90 years) while Dustman, Shearer and Snyder (1982) concluded that age-related amplitude changes were confined to developmental years (below the age of 14). LaMarche et al (1986) found that old females had significantly larger amplitudes than old males, young males or young females (these three groups were also compared and showed no significant differences). Since this type of stimulus involves both pattern and luminance changes the interpretation of the results is somewhat problematic.

Pattern VER

An example of a stimulus which involves only changes in contrast as opposed to luminance changes is reversal of a checkerboard as used in the largest number of age-related studies. For instance, Kazis, Vlaikidis, Pappa, Papanastasiou, Vlahveis and Routsonis (1983) measured a mean latency of 115 msec in old subjects (mean age 78.5 years) and a mean latency of 96 msec in young subjects (mean age 30.5 years). Narayan and Kooi (1984) obtained similar results with the additional interesting finding that the latency difference in young and old observers was due to young females having a latency (98 msec) significantly shorter than that of young males (104 msec) and that of both elderly males and females (106 and 104 msec respectively). Halliday, Barrett, Carroll and Kriss (1982) reported similar sex differences; age significantly affected latency only in female subjects (increasing from *ca* 103 msec in the fifth decade to *ca* 109 msec in the seventh decade). Shaw and Cant (1981) also found sex differences in the latency changes but, in contrast with the above studies, concluded that males showed a greater ageing effect than females. On the other hand, Wright, Williams, Drasdo and Harding (1985) found no difference in the pattern VER between male and female subjects. Age effects *were* apparent, however, with a significant increase in latency being present in the older age groups. Kriss et al (1984) found age-related latency increases in all components with both pattern reversal and onset, while Mitchell, Howe and Spencer (1987) noted an increase in P100 latency with age. In the study carried out by Stockard, Hughes and Sharbrough (1979), using pattern reversal of rectangular checks, the fact that no significant age-related latency changes were present was attributed to the sampling range (second to fifth decade) since there was a slight increase in P1 latency in the oldest subjects. Trick, Trick and Haywood (1986) also found no significant latency effects (20 to 30 years compared with 70 to 80 years) although there was a slight non-significant increase in latency in the old subjects.

Although it has often been shown that increasing age is accompanied by an increase in the latency of the VER, the age at which this effect manifests itself has varied from study to study. P100 (the positive component of the waveform evoked by checkerboard pattern reversal and seen after approximately 100 msec) has been observed to behave differently in different laboratories: Celesia and Daly (1977) reported an increase in P100 latency from age 20 onwards (or, more precisely, reported that the data could be fitted by a linear regression from this age upwards); Shaw and Cant (1980) observed that the latency of P100 increased only after the fourth decade; Kjaer (1980) found that P100 latency was increased above the age of 50; Asselman, Chadwick and Marsden (1975) and Allison, Wood and Goff (1983) found that the increase occurred only after age 60; Hennerici, Wenzel and Freund (1977) also found that latency remained unchanged into the mid-sixties. According to Shaw (1984) the latency changes observed in certain VER components first become apparent at different ages: P1 (55-65 msec) and N1 (70-80 msec) showed an increase in latency only above the age of 50 yrs, while P2 (100-110 msec - P100 in the above studies) and N2 (135-160 msec) gradually increased in latency from 20 yrs upwards.

A close look at the stimulus conditions reveals an important difference between some of the above studies. The work carried out by Celesia and Daly, the results of which seem to be particularly at odds with the others, used a checkerboard pattern with squares of size 15.5 min arc, a pattern of a much higher spatial frequency than those used in the study of Shaw and Cant (50 min arc), of Allison et al (50 min arc), of Kjaer (50 min arc), of Asselman et al (57 min arc) and of Hennerici et al (1 deg 10 min arc). As Sokol, Moskowitz and Towle (1981) have shown, the age-related changes in the VER latency are more pronounced when the stimulus used is of a higher spatial frequency (as, in that particular study, checkerboard squares of side 12 min arc compared with those of 48 min arc). Wright et al (1985) also found that the latency increase was more marked with smaller checks, while Celesia, Kaufman and Cone (1987) observed age-related latency increases only with a pattern containing 15 min checks and not when 31 min checks were used.

Although Shaw and Cant (1980) showed that these latency changes with advancing age were affected by the luminance of the pattern (i.e. the age-dependent latency increase was not obvious when a high luminance was used), this is not always borne out when the results from the other studies are examined. For example, Asselman et al (1975) and Hennerici et al (1977), while obtaining similar results, used patterns of markedly different luminance (Asselman et al used white squares of luminance 1929 cd/m^2; Hennerici et al used white squares of luminance 51.39 cd/m^2).

Snyder, Dustman and Shearer (1981), using checkerboard reversal as the stimulus, found no significant changes in the VER amplitude from adolescence to old age, although a decrease in amplitude from childhood to adolescence was observed (ages of subjects ranged from 4 to 90 years), Celesia and Daly (1977) could also find no amplitude changes within the age range tested (18-79 years), while the same was true for Halliday et al (1982) who found that, although females had significantly larger amplitudes than males at all ages, there were no significant age-related amplitude changes. Wright et al (1985) found that, although amplitudes were higher in teenagers, there were no consistent effects in adulthood. This study also used checkerboard onset as the stimulus and found similar trends in amplitude (and latency) as had been seen with pattern reversal. Similar conclusions (no significant age-related amplitude effects) were drawn by Hennerici et al (1977), Kjaer (1980), Kazis et al (1983), and Mitchell et al (1987), all using checkerboard reversal. By contrast, LaMarche et al (1986) found that the amplitude of the P100-N150 complex was significantly larger in old subjects (primarily because of its significantly larger amplitude in older females). Allison, Hume, Wood and Goff (1984), on the other hand, found that amplitude tended to decrease with age (4-95 years), with the greatest effect occurring in pre-adolescence. Trick et al (1986) also reported a reduced amplitude with age. In the study carried out by Shaw and Cant (1981), the amplitude of P100 was found to vary with age in a non-linear manner, being maximal in childhood, declining until the fourth decade, increasing again and then declining once more after the sixth decade.

In summarising the results of age-related VER studies the main effect of age would seem to be a general prolongation of latency. With an unpatterned flash the effects on amplitude are variable while with checkerboard pattern reversal there generally appear to be no amplitude changes with age (see Table 5).

TABLE 5. Summary of previous studies on the effects of ageing on the latency and amplitude of the VER.

	STIMULUS	**LATENCY**	**AMPLITUDE**
COPENHAVER & PERRY (1964)	*	-	↓
STRAUMANIS et al (1965)	*	↑	↑
DUSTMAN & BECK (1966, 1969)	*	↑	↑
BUCHSBAUM et al (1974)	*	↑	↓
DUSTMAN et al (1977)	*	↑	↑
MAN'KOVSKII et al (1978)	*	↑	↑↓[8]
COSI et al (1982)	*	↑	↑
DUSTMAN & SNYDER (1981)	⊙	↓[1]	↑
DUSTMAN et al (1982)	⊙	↓[1]	-
ASSELMAN et al (1975)	†	↑	-
CELESIA & DALY (1977)	†	↑	no change
HENNERICI et al (1977)	†	no change	no change
STOCKARD et al (1979)	†	no change[2]	-
KJAER (1980)	†	↑	no change
SHAW & CANT (1980)	†	↑[3]	-
SHAW & CANT (1981)	†	-	↓[9]
SNYDER et al (1981)	†	-	no change
SOKOL et al (1981)	†	↑[4]	-
HALLIDAY et al (1982)	†	↑[5]	no change
ALLISON et al (1983)	†	↑	-
KAZIS et al (1983)	†	↑	no change
ALLISON et al (1984)	†	↑	↓
KRISS et al (1984)	†⊗	↑	↑↓[10]
NARAYAN et al (1984)	†	↑[6]	-
SHAW (1984)	†	↑[7]	-
WRIGHT et al (1985)	†*⊗	↑	no change
LAMARCHE et al (1986)	†*⊙	-	↑[11]
TRICK et al (1986)	†	no change	↓
CELESIA et al (1987)	†	↑	-
MITCHELL et al (1987)	†	↑	no change

† checkerboard reversal
* unpatterned flash
⊙ checkerboard flash
⊗ checkerboard onset

[1] largely due to long latencies in children
[2] age range: 13-67yrs
[3] accentuated at low luminances
[4] accentuated with small checks
[5] in females only
[6] because shorter in young females
[7] P1 & N1 - ↑ above 50 yrs; P2 & N2 - ↑ above 20 yrs
[8] early components ↑; late components ↓
[9] non-linear relationship
[10] increase for onset; decrease for reversal
[11] in females only (and not with unpatterned flash)

The checkerboard has been the only type of patterned stimulus to be used in age-related VER studies but it is debatable as to whether it is the most suitable. The sinusoidal grating pattern is the simplest spatially ordered stimulus available yet it has never been used in age-related electrophysiological studies. The evidence which has been amassed suggests that the visual system operates through the action of different 'channels' selectively sensitive to particular spatial frequencies (see General Introduction). Since a great number of psychophysical investigations use sine-wave gratings as the stimulus it is clear that in any attempt to correlate the psychophysical age-related decline in contrast sensitivity with concommitant electrophysiological changes the same type of stimulus should be used.

Checkerboard stimuli give bigger responses than do grating patterns but the fact that the checkerboard pattern is the more complex of the two (containing higher harmonic components and having a fundamental frequency which lies along the diagonal of the display) it is perhaps more difficult to relate stimulus variables to response characteristics. In addition, the checkerboard VER is more sensitive to the effects of defocus than is the grating PVER (Boback, Bodis-Wollner and Guillory, 1987). In the studies on ageing, the checkerboard patterns were generally of a fixed contrast and, bearing in mind the age-related differences in contrast sensitivity, it is apparent that the older subjects would be disadvantaged by the fact that the stimuli were not psychophysically equivalent. In addition, these studies used stimuli at very high contrasts where there is the possibility of PVER saturation (Kulikowski, 1977) with resulting difficulties of comparison.

In the present study, therefore, it was decided to investigate the effects of ageing on the cortical response evoked by the onset of sinusoidal grating patterns of 3 c/deg and 8 c/deg; the former should primarily excite transient channels while the latter should be processed by sustained channels (Tolhurst, 1973; see General Introduction). In the first part of the following section the stimuli were vertical sinusoidal grating patterns of spatial frequency 3 and 8 c/deg presented at a range of contrasts from 3-40%, and grating patterns of spatial frequencies from 1-15 c/deg presented at 40% contrast. In the second part the stimuli were grating patterns of 3 and 8 c/deg presented at a range of contrasts which were multiples of the subject's pre-determined contrast threshold and hence were psychophysically equivalent. It was not possible to use a spatial frequency higher than 8 c/deg (and hence more firmly in the 'sustained' range) since the higher contrast thresholds would have restricted the range of contrast multiples which could have been used.

In addition, an unpatterned flash stimulus was also employed.

A previous report of part of this work appeared in Chalmers, Morrison, Ogg and Reilly (1985), and Morrison and Reilly (1989).

METHODS

STIMULUS DISPLAYS

Section 1

The stimulus used was a vertical sinusoidal grating pattern generated on a Telequipment DM53S oscilloscope with a P31 phosphor and peak wavelength of 520nm. A raster was produced by feeding a 100KHz triangular wave into the vertical amplifier with the time base running at 0.5 msec/div. This was modulated by a sine wave from a Feedback oscillator fed into the Z modulation of the oscilloscope. The frequency and amplitude of the sine wave was monitored on a Tektronix 5103 oscilloscope. The luminance of the Telequipment oscilloscope screen was 1.45 cd/m^2. The contrast of the sine wave grating, given by the formula $(L^{max} - L^{min}) / (L^{max} + L^{min})$, was determined by three subjects using Campbell and Green's (1965) contrast matching technique (see SDT Methods). Contrast was linearly related to the Z modulation voltage (1 contrast unit / volt peak-to-peak; see Figure 2 in Appendix).

The screen, which was viewed through a window in green cardboard, subtended either 1.5 or 4.5 deg arc depending on the viewing distance, 3m and 1m respectively. In order to investigate the effects of varying stimulus contrast on the pattern VER, a range of contrasts was used at two particular spatial frequencies: 3 c/deg and 8 c/deg, both viewed at the near distance. The former was chosen because it lies at the peak of the contrast sensitivity function; the latter was chosen because, although being a medium-moderately high spatial frequency, its threshold was sufficiently low as to allow stimuli of relatively low physical contrasts to be used while still evoking a clearly discernible response. In addition, the lower spatial frequency stimulus should be processed by transient channels while the higher spatial frequency should be processed by sustained channels (Tolhurst, 1973). The contrasts which were used were: 3%, 5%, 10%, 20% and 40%. Evoked responses were also recorded to a range of spatial frequencies: 1, 2, 3, 5, 8, 10 and 15 c/deg. The first five were viewed at the near distance, the latter two at the far distance. Contrast of the pattern was 40%.

Section 2

The stimulus (again a vertical sinusoidal grating pattern) was generated on a Tektronix 606B monitor in the same manner as in SDT Methods. The contrast of the pattern was determined psychophysically by three different observers and was found to be linearly related to the Z-modulation voltage (0.25 contrast units / volt peak-peak up to 1.5V, maximum contrast of 0.8; see Figure 3 in Appendix).

The aim of this part of the study was to relate evoked response parameters to stimulus contrasts which were set with reference to each subject's individual psychophysical threshold. Two spatial frequencies were used: 3c/deg and 8c/deg. Viewing distance was 1.43m with a screen size of 4 deg arc. Contrast thresholds for these spatial frequencies were determined using an ascending method (as described in SDT Methods). The stimuli used were presented at multiples of this threshold. In young subjects the multiples used were, typically: 50x, 20x, 10x, 5x and 3x threshold. Contrasts lower than the above were sometimes used in order to present stimuli which were as near to the subject's threshold as possible while still evoking a reasonably clear response. Intermediate contrast multiples were sometimes used. In old subjects, the higher contrast thresholds placed a restriction on the range of contrast multiples which could be used and hence the latter were tailored for each individual to allow as wide a range as possible to be used.

In both Sections the grating pattern was present for 0.5 sec and was alternated with a uniform screen of the same mean luminance present for 1.0 sec. The stimulus was of the above duration in order that a full transient PVER might have time to develop. The inter-stimulus interval was such as to ensure minimum physiological adaptation effects (Jackson and Barber, 1980). Pattern onset was chosen rather than pattern reversal since responses to the latter are known to be more contaminated by luminance components (Jeffreys, 1977). Prior to experimentation a psychophysical method was used in order to verify that there was no mean luminance change on stimulus presentation: no luminance change was noted when pattern onset was viewed through a diffuser nor when onset of a very fine pattern beyond the limit of resolution was observed.

A problem which was occasionally encountered in Section 1 was the entrainment of the alpha rhythm by the stimulus presentation and the failure of low contrast patterns to desynchronize or block this alpha rhythm. In Section 2, the mode of grating pattern presentation was slightly modified in an attempt to deal with this problem. The cycle was lengthened to 3050 msec and within each cycle the pattern was presented twice. The first presentation was after 1000 msec and the second after 2550 msec (both lasting 500 msec). The 50 msec difference in inter-stimulus intervals meant that the grating pattern presentation was not as rhythmic as before. In most cases, aperiodic presentation appeared to be sufficient to desynchronize the alpha rhythm and it was less regularly recorded when this method of stimulation was used.

A Devices Digitimer triggered the simultaneous onset of both the stimulus presentation and the period of sampling by the microcomputer via a -12V to +5V conditioning unit (Fig. 30). A trial was comprised of 50 presentations. Repeat runs were made in order to monitor the reproducibility of responses (see Figures 4 and 5 in Appendix). Control runs where the subject looked at a uniform screen for the duration of the trial were also recorded.

Section 3

The stimulus was a brief Xenon flash from a Devices photic stimulator (type 3181) housed in a 6½in diameter reflector bowl with a green diffusing filter. The circular screen was masked with black tape to give a rectangular display. The width subtended by the window was 3.0 deg while the height was 2.4 deg.

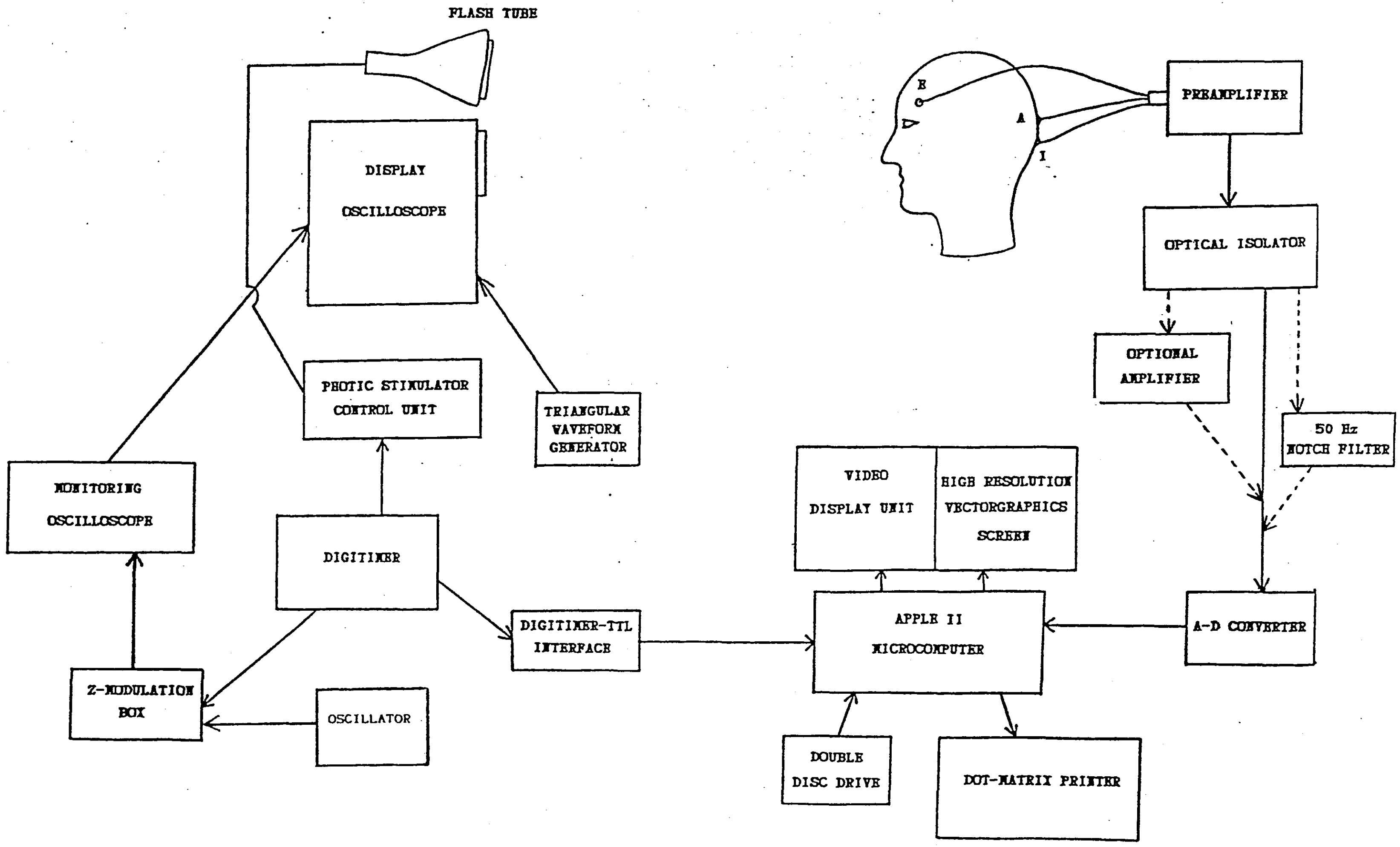


FIGURE 30. Schematic representation of experimental set-up for recording of visually evoked responses elicited by flash and pattern presentation.

Five intensity levels could be employed. The nominal peak luminance at the highest intensity was 1.0 x 10^7cd/m^2 while that of the lowest intensity flash was 9.0 x 10^5cd/m^2. The peak output was reached in approximately 4 microseconds with an exponential decay to 1/e of peak intensity by approximately 25 microseconds. In order to calibrate the five intensity levels with respect to photopic threshold, a psychophysical technique was used whereby a range of neutral density filters were placed in front of the display in order to determine the minimum value of filter which screened the flash from a young observer. Three subjects participated and it was found that the stimuli were *ca* 4.1, 4.4, 4.9, 5.2 and 6.1 log units above photopic threshold. The effects of varying flash intensity on the VER were investigated in a group of young subjects. In the study on ageing only the maximum intensity flash was routinely used. This was generally done prior to the trials involving grating pattern presentation in order to check the integrity of the recording set-up using a powerful stimulus. The temporal frequency of stimulation was one flash every 1.5 secs (0.67Hz).

RECORDING

The areas of the scalp and forehead to which the electrodes were to be attached were first vigorously cleaned with alcohol. Neptic electrode gel was then rubbed into the skin to provide better electrical contact. Finally, some Grass electrode cream was applied, both to the skin and to the electrodes which were then fixed in place. Electrode cream was preferred to collodion-applied electrodes for convenience of application and ease of removal. No difference was found in the electrical records obtained using each method (see Figure 6 in Appendix).

Two recording configurations were evaluated. The most frequently used set-up utilized three Ag-AgCl cup electrodes. The active electrode was placed approximately 3cm above the inion on the area overlying the visual cortex (a position roughly 10% of the distance between the inion and the nasion and corresponding to site O_z in the International 10/20 system). The reference electrode was positioned on the inion itself and the earth electrode was placed on the forehead. In the second, less frequently used method only two electrodes were employed, the active electrode in the same site as above and referenced to the forehead. Both methods yielded highly comparable recordings (see Figure 7 in Appendix) and the results were combined for analysis. In Section 2, the three-electrode configuration was always used. The electrodes were chlorided prior to each recording session.

SIGNAL AVERAGING

The signal was passed into a preamplifier of bandwidth 2-60 Hz (1200x amplification) and from there onto a phase-locked loop optical isolator which served to isolate the subject from the mains-driven equipment and also provided further amplification (up to a total of 70,000x). An additional amplifier (x10 or x100) could be used if the signal was especially small. A 50Hz notch filter was also occasionally used in those instances where mains noise was disrupting the recording. The signal was fed into one channel of an A1-02 analogue-to-digital (A/D) converter with a resolution of 8 bits, a sample aperture of 70 μsec and a maximum input of ±5V. From here the signal was passed into an Apple 11 plus microcomputer. The A/D converter was powered by a stabilized +5.00V supply derived from the microcomputer's +12V line since its own +5V supply was not sufficiently stable for the purpose (Fig. 29).

The VER was averaged from 50 sweeps. This number of samples was found to be a reasonable compromise between the number of presentations required for a clear summated response and the number of presentations over which the subject could maintain concentration. However, the program allowed individual files to be added together giving grand-averaged waveforms.

The averaging program was written in machine code and hence provided a very fast operation. Sampling rate could be modified although bin width (interval between samples) was usually set at 0.8 or 1.0msec. There were 500 sampling points in each sweep and hence the total sampling time was 400 or 500msec from stimulus onset. The use of a Digisolve Vector Graphic board and a high resolution monitor allowed on-line observation of individual responses. The facility to reject obviously deviating waveforms (i.e. those drifting off-scale) was available and could be used if, for example, a subject's movement disturbed the electrode during a particular presentation.

The evoked response was stored as a file on floppy disc for subsequent print-out and analysis. If noise was present in the final averaged response then the program allowed first order smoothing of the waveform.

SUBJECTS

Volunteers were recruited in the same manner as for the SDT study. Most of the young subjects came from within the Institute of Physiology, Glasgow University, while the majority of older subjects were from local Senior Citizens' Groups. In many cases, subjects who participated in the signal detection experiments also took part in the VER study. Prior to the recording session, visual acuity was tested in all subjects. In Sections 1 and 3, this was done using a Snellen wallchart viewed directly from 5 metres; in section 2, a back-illuminated Snellen chart was used, viewed from the same distance. All subjects had normal acuity for their age and wore appropriate correcting lenses if required. Subjects were also tested and corrected for astigmatism.

In Section 1, in which were investigated the effects of different contrasts and spatial frequencies on the pattern VER, the 23 young subjects ranged in age from 15 to 34 years with a mean age of 22.1 yrs. There were 15 male subjects (2 subjects in their teens, 12 in their 20s, 1 in his 30s) with a mean age of 22.5 yrs. All 8 female subjects were in their 20s (mean age 21.3 yrs). In the 22 older subjects, the age distribution was as follows : 50s (3 male, 3 female); 60s (3 male, 2 female); 70s (5 male, 2 female); 80s (2 male, 2 female). Mean age was 67.8 yrs (67.9 yrs in male subjects, 67.6 yrs in female subjects).

In Section 2, the effects on the PVER of a range of contrasts relative to psychophysical threshold were investigated. The 11 young subjects had a mean age of 22.5 yrs and ranged in age from 17 to 27 yrs. The mean age of the 7 male subjects (1 in teens, 6 in 20s) was 22.6 yrs while the mean age of the 4 female subjects (1 in teens, 3 in 20s) was 22.5 years. In the 9 older subjects, the ages ranged from 74 to 94 yrs. The age distribution was as follows: 70s (2 male, 2 female), 80s (1 female), 90s (2 male, 2 female). Mean age of the older group was 84.2 yrs (84.5 yrs in males, 84 yrs in females).

In Section 3, the effects of a range of flash intensities on the VER were studied in a group of 13 young subjects (mean age 22 yrs, range 17 to 27 yrs). For seven of these subjects all five of the flash intensities were used; for the remaining six subjects only three intensities were used: the highest, the lowest and the intermediate. In the study on ageing only the highest intensity was used. In this case, 10 young subjects (7 male and 3 female) with a mean age of 22.4 yrs and ranging in age from 20 to 27 yrs were tested. The 10 old subjects (6 female and 4 male) who were tested ranged in age from 53 to 82 yrs and had a mean age of 71 yrs.

The subject sat on a height-adjustable chair inside an earthed Faraday cage with a window cut in the front through which the stimulus displays could be viewed. A sheet of metal on the floor beneath the subject and connected to the cage meant that the subject was screened from all directions. On some occasions the subject's head was supported by a chin rest. The room was in darkness during the recording period. Stimulation was binocular using natural pupil diameters.

During each experimental run the subject was asked to fixate on the centre of the stimulus field (i.e. maintain their gaze in the direction of the flash or, in the case of the grating pattern in Section 1, keep their eyes fixed on a small marker positioned in the centre of the oscilloscope screen).

It has been suggested that upper and lower hemi-field responses may contain components of opposite polarity which may cancel each other out when both are evoked simultaneously as in full-field checkerboard stimulation (Lesèvre and Joseph, 1980). Using a grating pattern stimulus, Parker and Salzen (1977a) showed that with upper-field stimulation the response was almost completely abolished. In Section 2, therefore, the fixation point was positioned at the top of the oscilloscope screen. Hence, in this instance only lower-field stimulation was being used.

Subjects were requested to refrain from moving, blinking, yawning, etc. Attention was maintained by counting the number of stimulus presentations. Between runs the subject was instructed to close his or her eyes or to look away from the screen to avoid development of after-images.

ANALYSIS

Three features of the visually evoked response were measured and analysed: amplitude, latency (to peak), and rise time (Fig. 31).

The first of these, amplitude, was measured from the peak of the previous waveform component to the peak of the component in question. When the component under analysis was the first to appear after stimulus onset then the amplitude was measured from the point of component onset to its peak.

Latency to peak was measured from the stimulus onset to the time at which the response component reached its peak.

Rise time was measured from the time at the peak of the previous component to the time at the peak of the component under analysis.

In a considerable number of instances the presence of noise in the response meant that the component had no clearly defined peak. In order to facilitate analysis the approximate mid-point of the waveform's plateau was determined and regarded as the time at which the peak would lie. In the case of amplitude, when no single peak existed then a measurement was made between the component plateaux (Fig. 31).

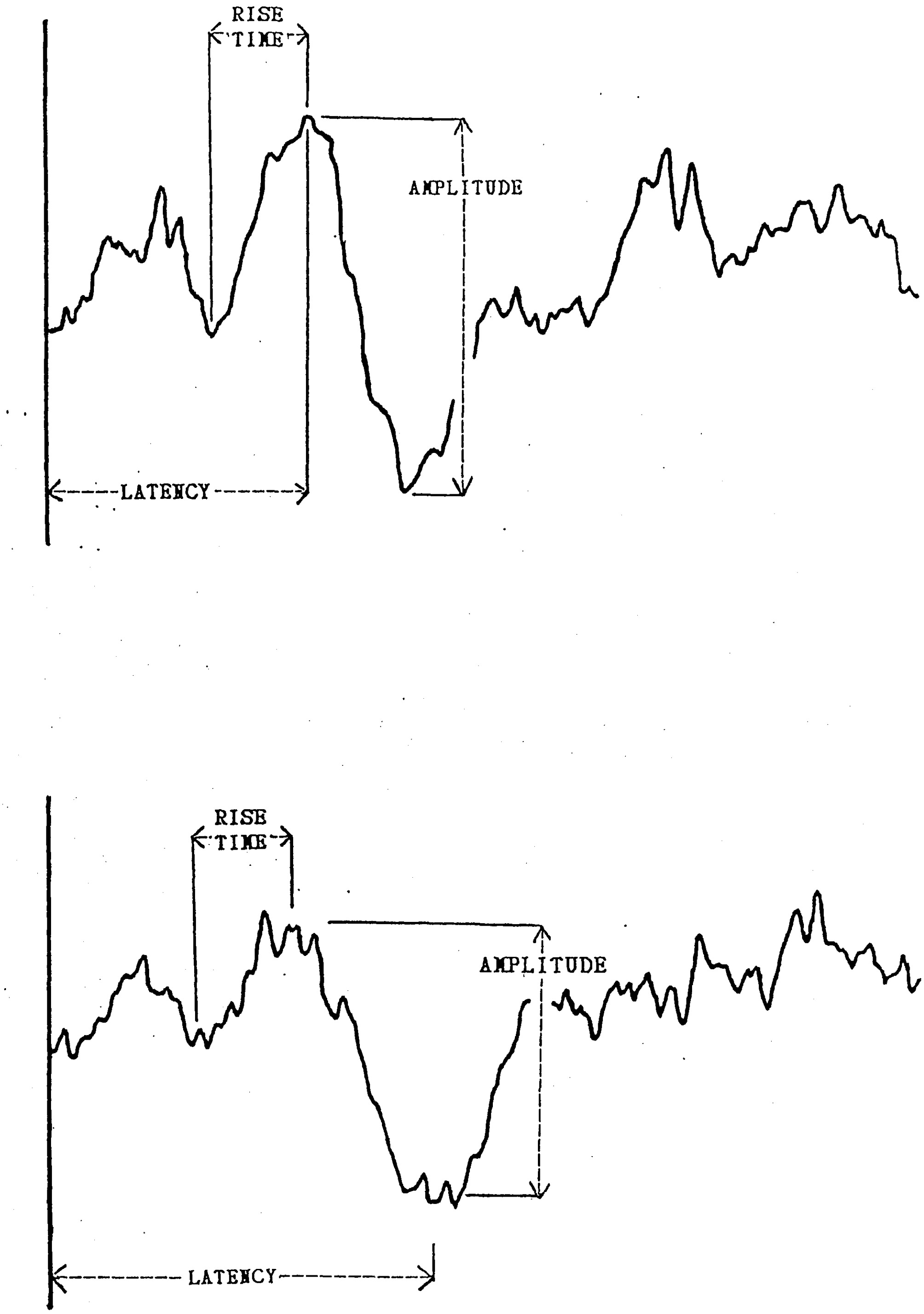


FIGURE 31. Features of the VER which were analyzed. Lower waveform shows method of measurement when position of component peaks is ambiguous.

The latency, amplitude and rise time data of young and old groups were compared using a *t*-test. The significance of the relationship of VER latency, amplitude and rise time with contrast or contrast multiple was assessed using linear regression. Comparison was also made between the intercepts and slopes of the best-fitting regression equations in young and old subjects (Draper and Smith, 1981).

[illegible] to [illegible] for their part[illegible]

[illegible]

The waveform evoked by the onset of a vertic[illegible] grating pattern (Fig. 32) contained a promi[illegible] deflection (N1) occurring at *ca* 100 msec and f[illegible] positive wave (P1) with a latency to peak of *ca* [illegible] second negative component (N2) was present at aro[illegible] while a second positivity (P2) occurred at *ca* 2[illegible] precise values of the component latencies were a[illegible] stimulus characteristics and by subject age (see [illegible] times tended to be longer for each consecutive com[illegible] temporal sequence (i.e. rise time of P2 > N2 [illegible] amplitudes of N2 and P2 tended to be greater than [illegible] two earlier components (although this [illegible] and subjects). Relative amplitudes of peaks varied between subjects of similar ages.

RESULTS

Snellen acuities for all subjects were found to be within the normal range for their particular age group (Weale, 1975).

1. PATTERN VER AND PHYSICAL CONTRAST

The waveform evoked by the onset of a vertical sinusoidal grating pattern (Fig. 32) contained a prominent negative deflection (N1) occurring at *ca* 100 msec and followed by a positive wave (P1) with a latency to peak of *ca* 150 msec. A second negative component (N2) was present at around 220 msec, while a second positivity (P2) occurred at *ca* 280 msec. The precise values of the component latencies were affected by stimulus characteristics and by subject age (see later). Rise times tended to be longer for each consecutive component in the temporal sequence (i.e. rise time of P2 > N2 > P1 > N1). Amplitudes of N2 and P2 tended to be greater than those of the two earlier components (although this trend was less marked in old subjects). Relative amplitudes of peaks varied substantially between subjects of similar ages.

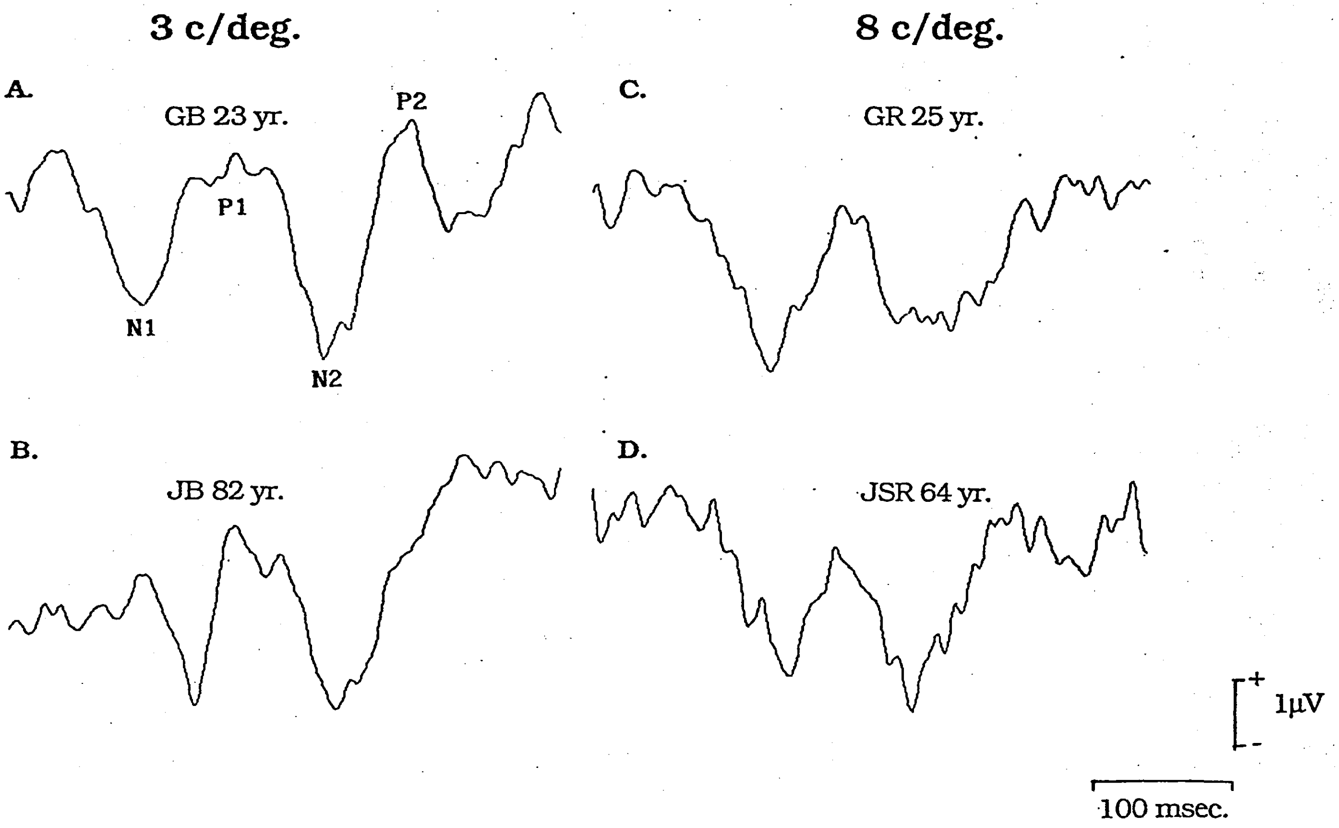


FIGURE 32. Typical VERs in young and old subjects to onset of grating patterns of 40% contrast and spatial frequencies 3 c/deg (A & B) and 8 c/deg (C & D).

(i) Effects of varying physical contrast

Evoked responses were recorded in young and old subjects to the onset of vertical sinusoidal grating patterns of 3 and 8 c/deg and contrasts 3, 5, 10, 20 and 40%. Typical records demonstrating the manner in which the PVER varied with contrast are shown in Figure 33. The most obvious change with a reduction in contrast is the shift of the response to the right indicating an increase in the latency of the components. Neither amplitude nor rise time show any obvious change with contrast.

Latency

For both young and old subjects and at both 3 and 8 c/deg, linear regressions were made of latency against both contrast and logarithm contrast. In virtually all instances the correlation was greater when logarithm contrast was used.

3 c/deg

Comparisons of latency were made between male and female subjects at 40% contrast for both spatial frequencies and for both young and old groups. No significant sex differences were found ($p>0.1$) and the data were combined and analysed collectively.

In both young and old subjects, the latencies of N1, P1 and N2 were significantly inversely correlated with log contrast. P2 latency was not significantly correlated with log contrast (Fig. 34 and Table 6).

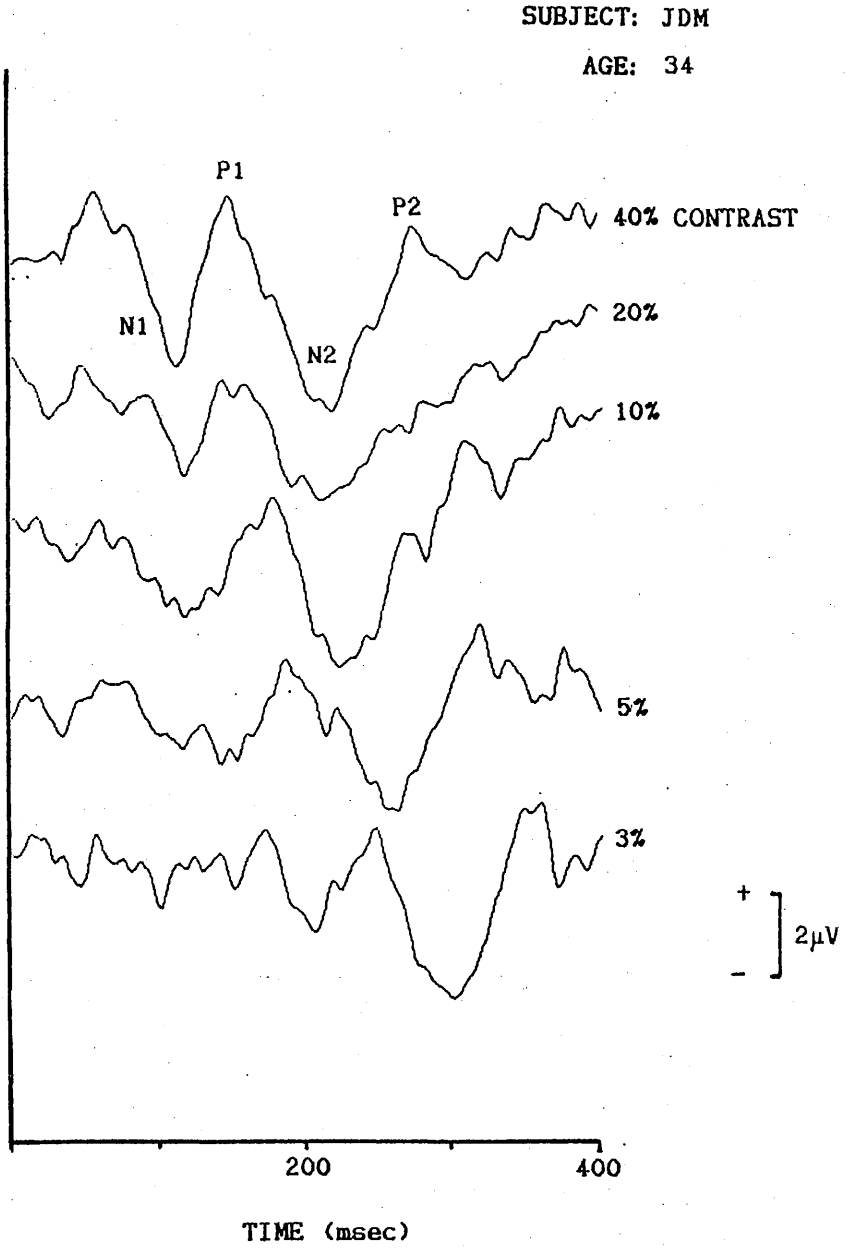


FIGURE 33. Effect of varying contrast on the VER to onset of a 3 c/deg grating pattern.

3 c/deg.

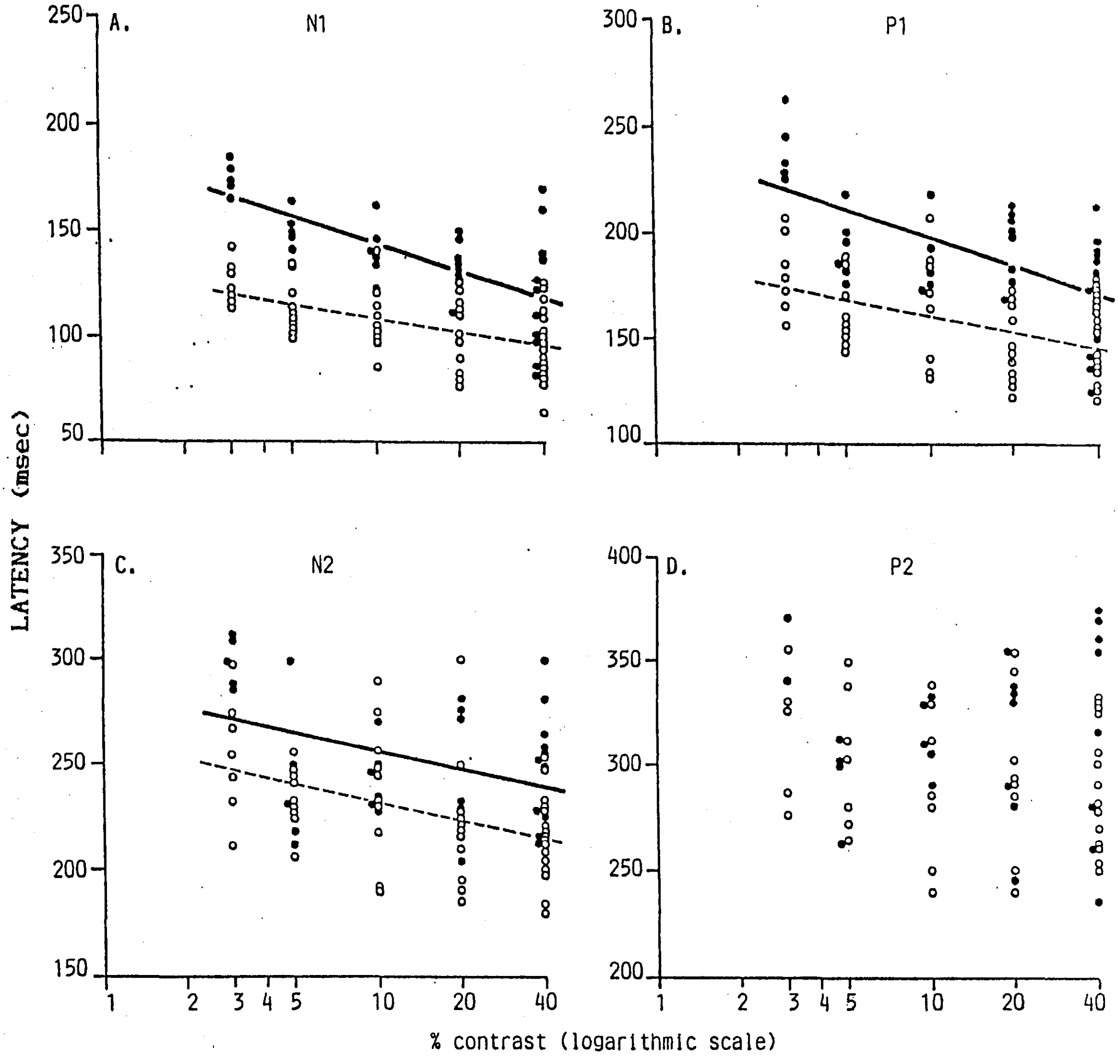


FIGURE 34. Effect of varying the contrast of a 3 c/deg grating pattern on the latency of N1, P1, N2 and P2 components of the transient PVER. Young subjects are shown by unfilled circles, with corresponding regression equation represented by dashed line; old subjects are shown by filled circle with corresponding regression equation by solid line.

TABLE 6 Dependence of PVER latency on log contrast at 3 c/deg.

		CONTRAST (%)							
		40	20	10	5	3	$\overline{SE}$	*r*	*p*
N1	Young	97	101	108	111	125	*±5*	*-0.51*	*<0.01*
	Old	121	134	141	149	176	*±5*	*-0.68*	*<0.001*
		*	*	*	*	*			
P1	Young	150	146	164	162	180	*±6*	*-0.46*	*<0.01*
	Old	171	193	188	193	239	*±7*	*-0.62*	*<0.001*
		*	*	NS	*	*			
N2	Young	215	221	238	234	255	*±8*	*-0.45*	*<0.01*
	Old	243	249	244	242	299	*±10*	*-0.37*	*<0.05*
		*	+	NS	NS	*			
P2	Young	290	295	291	303	315	*±13*	*-0.21*	*>0.1*
	Old	319	310	313	294	355	*±13*	*-0.01*	*>0.9*
		NS	NS	NS	NS	-			

Table shows correlation coefficient (*r*) of latency (msec) against log contrast, and level of significance (*p*), Comparisons between young and old at each contrast by *t*-test are also shown, NS not significant; + $0.05<p<0.1$; * $p<0.05$.

Mean latencies of N1, P1, N2 and P2 were consistently shorter in the young group (Table 6 and *cf* Figs 32A and B). Only in one instance, P2 at 5% contrast, was the opposite the case. The latency of N1 was significantly shorter in young subjects at each of the five contrasts. The P1 component was also significantly shorter in young subjects except at 10% contrast where the difference was not significant. For the N2 component, significant differences occurred in only two instances, at 40% and 3% contrast, while at 20% contrast a difference of marginal significance was present. No significant age-related differences in latency were found with the P2 component. For P2 at 3% contrast, the small number of subjects in the old group precluded statistical analysis.

Statistical comparisons were made of the intercepts of the corresponding regression equations in young and old subjects. This was done at a point of reference common to both age groups: the intercept with the line drawn at the mean stimulus contrast for *all* subjects. For N1, P1 and N2 these intercepts were found to be significantly different in the two groups (Table 7).

In order to investigate whether there was any age-related difference in the 'gain' of the system, a statistical comparison was made of the slopes of the corresponding regression equations in young and old subjects. Although a visual inspection suggested that the slopes of the regression lines of N1 and P1 latency against log contrast were slightly steeper in old subjects (Fig. 34), a statistical test showed no significant differences between the age groups for these two components and for N2 (Table 7).

TABLE 7 Comparison of intercepts and slopes of regression equations of PVER latency against log contrast at 3 c/deg for young and old subjects.

INTERCEPTS

	N1	P1	N2
YOUNG	105	158	229
OLD	140	192	253
p	<0.001	<0.001	<0.01

SLOPES

	N1	P1	N2
YOUNG	-21.7	-24.3	-31.2
OLD	-41.7	-43.8	-29.8
p	>0.25	>0.25	>0.25

8 c/deg

For both age groups, the latencies of N1, P1 and N2 were significantly inversely correlated with log contrast. P2 latency showed no significant correlation with log contrast (Fig. 35 and Table 8).

The mean latency at a given contrast was always of a numerically higher value in old subjects than it was in young (Table 8 and *cf* Figs 32C and D). However, the difference was not always significant. At each of the contrasts, both N1 and P1 latencies were significantly shorter in the young age group. For the N2 component, significant differences were present at 40%, 20% and 5% contrast, while for the P2 component there were no significant age-related differences. For P2 at 5% contrast the small number of points in the old group precluded statistical analysis. In the old subjects, a stimulus of 3% contrast did not evoke a clearly discernible waveform.

By visual inspection of the data, the slopes of the regression lines for N1, P1 and N2 appeared to be similar in young and old subjects (Fig. 35). Statistical comparisons showed no significant differences in the slopes of the corresponding lines in young and old subjects. Intercepts with the line drawn at the mean stimulus contrast were found to be significantly higher in old subjects (Table 9).

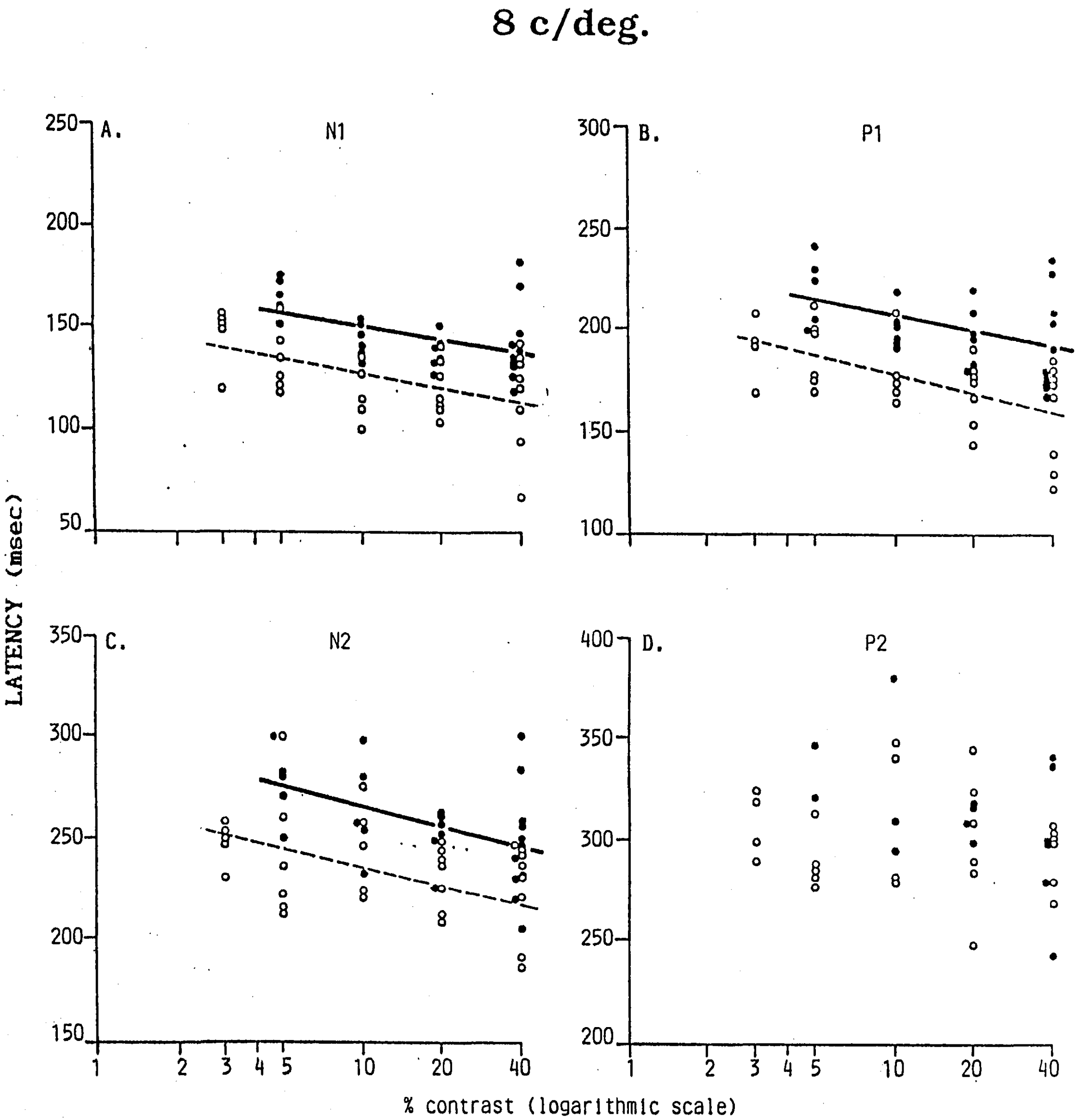


FIGURE 35. Effect of varying the contrast of an 8 c/deg grating pattern on the latency of N1, P1, N2 and P2 components of the transient PVER. Young subjects are shown by unfilled circles, with corresponding regression equation represented by dashed line; old subjects are shown by filled circles, with corresponding regression equation by solid line.

TABLE 8 Dependence of PVER latency on log contrast at 8 c/deg.

		CONTRAST (%)							
		40	20	10	5	3	$\overline{SE}$	*r*	*p*
	Young	116	120	117	133	145	±7	−0.49	<0.005
N1	Old	141	138	143	164	–	±5	−0.45	<0.05
		*	*	*	*				
	Young	159	170	178	188	191	±8	−0.57	<0.001
P1	Old	194	197	200	220	–	±6	−0.43	<0.05
		*	*	NS	*				
	Young	213	230	245	241	248	±9	−0.45	=0.01
N2	Old	247	251	247	276	–	±8	−0.45	<0.05
		*	*	NS	+				
	Young	279	301	313	290	309	±13	−0.24	>0.2
P2	Old	301	312	328	335	–	±15	−0.43	>0.1
		NS	NS	NS	–				

Table shows correlation coefficient (*r*) of latency (msec) against log contrast, and level of significance (*p*), Comparisons between young and old at each contrast by *t*-test are also shown, NS not significant; + 0,05<p<0,1; * p<0,05,

TABLE 9 Comparison of intercepts and slopes of regression equations of PVER latency against log contrast at 8 c/deg for young and old subjects.

INTERCEPTS

	N1	P1	N2
YOUNG	124	173	230
OLD	147	202	259
p	*<0.001*	*<0.001*	*<0.01*

SLOPES

	N1	P1	N2
YOUNG	-23.7	-29.8	-30.7
OLD	-21.2	-24.7	-31.7
p	*>0.25*	*>0.25*	*>0.25*

Comparison of regression equations for 3 and 8 c/deg

Within young and old groups, a comparison was made of the regression equations of latency against log contrast for 3 and 8 c/deg. This was done in order to determine whether the relationships were of the same form for the two spatial frequencies. In old subjects there were no significant differences between the corresponding regression equations for 3 and 8 c/deg in terms of either intercepts or slopes ($p>0.1$ and $p>0.25$ respectively). However, in young subjects the regression lines of both N1 and P1 had significantly different intercepts at

3 and 8 c/deg (p<0.001 in both cases) although the intercepts of N2 were not significantly different (p>0.25). In young subjects there were no significant differences in the slopes of the regression equations at the two spatial frequencies (p>0.25).

Rise time

There appeared to be no obvious relationship between rise time and contrast in both old and young subjects and at both spatial frequencies, an observation which was confirmed statistically (irrespective of whether contrast was expressed in linear or logarithmic units) (Tables 10 & 11). In old subjects at 8 c/deg the rise time of the P1 component was inversely correlated with log contrast with marginal significance.

Within young and old groups, comparisons of rise time were made between male and female subjects at 40% contrast for 3 c/deg and 8 c/deg. No significant sex differences were found (p>0.1) and hence the data were combined and analysed collectively.

With a 3 c/deg stimulus rise time showed no consistent age-related changes (Table 10 and *cf* Figs 32A and B). Only in two instances were significant differences observed: N1 at 20% contrast and P1 at 3% contrast had longer rise times in old subjects. In four instances, differences of marginal significance were present: at 40% and 5% contrast the N1 component of old subjects had a shorter rise time while at 10% contrast the same component had a longer rise time in old subjects. At 5% contrast the N2 component had a shorter rise time in old subjects.

TABLE 10 Dependence of PVER rise time on log contrast at 3 c/deg.

		CONTRAST (%)							
		40	20	10	5	3	$\overline{SE}$	*r*	*p*
N1	Young	40	23	27	36	36	*±3*	*0.05*	*>0.7*
	Old	30	39	37	33	34	*±4*	*−0.08*	*>0.6*
		+	*	+	+	NS			
P1	Young	52	45	46	53	46	*±5*	*0.04*	*>0.8*
	Old	49	56	46	44	63	*±5*	*−0.08*	*>0.6*
		NS	NS	NS	NS	*			
N2	Young	65	73	70	73	75	*±6*	*−0.15*	*>0.2*
	Old	72	54	55	50	60	*±8*	*0.24*	*>0.1*
		NS	NS	NS	+	NS			
P2	Young	71	71	51	66	58	*±7*	*0.20*	*>0.1*
	Old	72	61	66	66	62	*±9*	*0.11*	*>0.5*
		NS	NS	NS	NS	–			

Table shows correlation coefficient (*r*) of rise time (msec) against log contrast, and level of significance (*p*). Comparisons between young and old at each contrast by *t*-test are also shown. NS not significant; + $0.05<p<0.1$; * $p<0.05$. For P2, the small number of points in the old group at 3% contrast precluded statistical analysis.

With an 8 c/deg stimulus there were again no consistent differences in rise time between the two age groups (Table 11 and *cf* Figs 32C and D). Only in one case was there a significant difference present, at 10% contrast, where the rise time of N1 was significantly longer in old subjects.

TABLE 11 Dependence of PVER rise time on log contrast at 8 c/deg.

		CONTRAST (%)							
		40	20	10	5	3	$\overline{SE}$	*r*	*p*
	Young	32	31	27	30	34	±6	0.00	>0.9
N1	Old	34	43	42	37	–	±5	-0.13	>0.5
		NS	NS	*	NS				
	Young	45	50	60	55	45	±6	-0.17	>0.6
P1	Old	46	59	55	56	–	±4	-0.32	>0.05
		NS	NS	NS	NS				
	Young	53	60	66	50	49	±8	0.14	>0.5
N2	Old	54	52	64	55	–	±7	-0.23	>0.2
		NS	NS	NS	NS				
	Young	69	62	61	61	61	±11	0.13	>0.5
P2	Old	61	55	70	55	–	±10	-0.01	>0.9
		NS	NS	NS	–				

Table shows correlation coefficient (*r*) of rise time (msec) against log contrast, and level of significance (*p*). Comparisons between young and old at each contrast by *t*-test are also shown. NS not significant; * ($p<0.05$). For P2, the small number of points in the old group at 5% contrast precluded statistical analysis.

Amplitude

In young subjects at 8 c/deg and in old subjects at both spatial frequencies, there was no significant correlation between amplitude of any of the four components and stimulus contrast (Tables 12 & 13). In young subjects at 3 c/deg, a significant positive correlation was present between P2 amplitude and log contrast; the other components showed no significant correlation.

With a 3 c/deg pattern, there was a tendency, with only a few exceptions, for mean amplitude to be smaller in the old age group (Table 12). However, only with the N2 component at 5% contrast was the reduction significant. In four instances (N2 and P2 each at 40% and 20% contrast), the reduction in amplitude with age was of marginal significance.

With an 8 c/deg grating pattern, the mean amplitude of the old group was numerically smaller than that of young in all but one instance, N1 at 40% contrast (Table 13). Significant differences occurred at 5% contrast for N1, P1 and N2. Differences of marginal significance occurred at 20% contrast for N1 and at 20% and 10% contrast for P1.

TABLE 12 Dependence of PVER amplitude on log contrast at 3 c/deg.

		CONTRAST (%)							
		40	20	10	5	3	$\overline{SE}$	*r*	*p*
N1	Young	1.87	1.38	1.24	1.35	1.28	*±0.29*	*0.23*	*>0.1*
	Old	1.24	1.35	1.79	1.12	1.65	*±0.32*	*-0.11*	*>0.5*
		NS	NS	NS	NS	NS			
P1	Young	1.99	1.93	1.72	1.47	1.71	*±0.39*	*0.14*	*>0.6*
	Old	1.52	1.32	1.19	1.00	1.88	*±0.33*	*0.01*	*>0.9*
		NS	NS	NS	NS	NS			
N2	Young	2.74	3.43	1.98	2.17	2.03	*±0.50*	*0.21*	*>0.1*
	Old	1.77	1.68	1.21	0.66	1.78	*±0.38*	*0.19*	*>0.2*
		+	+	NS	*	NS			
P2	Young	2.75	3.00	1.85	1.63	1.29	*±0.60*	*0.43*	***<0.05***
	Old	1.54	1.59	1.79	1.78	1.78	*±0.63*	*-0.09*	*>0.6*
		+	+	NS	NS	-			

Table shows correlation coefficient (*r*) of amplitude (µV) against log contrast, and level of significance, Comparisons between young and old at each contrast by *t*-test are also shown, NS not significant; + (0,05<p<0,1); * p<0,05, For P2, the small number of data points in the old group at 3% contrast precluded statistical analysis,

TABLE 13 Dependence of PVER amplitude on log contrast at 8 c/deg.

		CONTRAST (%)							
		40	20	10	5	3	$\overline{SE}$	r	p
N1	Young	1.09	1.73	1.06	1.47	0.93	*±0.22*	*0.07*	*>0.7*
	Old	1.38	0.66	1.27	0.87	–	*±0.21*	*0.19*	*>0.6*
		NS	+	NS	*				
P1	Young	1.34	1.88	2.08	1.57	1.36	*±0.31*	*0.00*	*>0.9*
	Old	1.17	0.85	1.29	0.87	–	*±0.23*	*0.09*	*>0.6*
		NS	+	+	*				
N2	Young	1.68	1.89	2.14	1.76	1.68	*±0.36*	*0.00*	*>0.9*
	Old	1.18	1.02	1.49	0.81	–	*±0.34*	*0.07*	*>0.7*
		NS	NS	NS	*				
P2	Young	2.29	1.63	1.55	1.35	2.03	*±0.46*	*0.17*	*>0.5*
	Old	1.32	1.04	1.49	0.98	–	*±0.40*	*0.05*	*>0.8*
		NS	NS	NS	–				

Table shows correlation coefficient (*r*) of amplitude (µV) against log contrast, and level of significance, Comparisons between young and old at each contrast by *t*-test are also shown, NS not significant; + (0,05<p<0,1); * p<0,05, For P2, the small number of data points in the old group at 5% contrast precluded statistical analysis, Within young and old groups, comparisons of amplitude were made between male and female subjects at 40% contrast for both spatial frequencies. Some sex-related differences in amplitude were found (Table 14). In young subjects, N2 amplitude for 3 c/deg was significantly larger by 2x in males than in females ($p<0.05$); N1, N2 and P2 amplitudes at 8 c/deg were also significantly larger in males by 2-3x ($p<0.05$). In old subjects, however, the differences observed were in the opposite direction: for 3 c/deg, N1, P1 and N2 amplitudes were marginally significantly greater by 2x in females than in males ($0.05<p<0.1$), while for 8 c/deg, N1 amplitude was significantly greater by 2x in female subjects ($p<0.05$). All other components showed no significant sex differences ($p>0.1$).

Hence, as well as the collective analysis, data from males and females were also analysed separately.

At 3 c/deg, N1 and P1 amplitudes of old males were marginally significantly smaller by *ca* 50% than those of young males ($0.05<p<0.1$); N2 amplitude of old males was significantly smaller by *ca* 60% than that of young males ($p<0.01$). There were no significant age-related changes in the amplitude of P2 in men nor in N1, P1, N2 and P2 in women ($p>0.6$).

At 8 c/deg, N2 and P2 amplitudes of old males were marginally significantly smaller by *ca* 50% than those of young males ($0.05<p<0.1$). The amplitude of N1 was significantly larger by 4x in old females than in young females ($p<0.02$), while that of P1 was marginally significantly larger by 2x in old females (0.05<p<0.1). N1 and P1 in males and N2 and P2 in females showed no significant age-related changes (p>0.1).

Hence, in females there was a general trend towards an increase in amplitude with age, while for males the tendency was for a reduction in amplitude with age.

<u>**TABLE 14**</u> Mean amplitudes (µV ±SE) of components of PVER, in male and female subjects, elicited by 3 and 8 c/deg grating patterns at 40% contrast.

3 c/deg

		N1	P1	N2	P2
YOUNG	Male	1.91±0.4	2.39±0.5	3.43±0.5	2.85±0.6
	Female	1.82±0.4	1.53±0.3	1.84±0.4	2.65±0.4
		NS	NS	*	NS
OLD	Male	0.93±0.2	1.22±0.2	1.30±0.2	1.16±0.4
	Female	1.80±0.5	2.03±0.4	2.72±0.9	1.90±0.6
		+	+	+	NS

8 c/deg

		N1	P1	N2	P2
YOUNG	Male	1.44±0.2	1.72±0.4	2.11±0.3	3.18±0.5
	Female	0.48±0.1	0.71±0.3	0.97±0.3	1.88±0.4
		*	NS	*	*
OLD	Male	0.92±0.3	0.92±0.3	1.18±0.4	1.26±0.6
	Female	2.05±0.4	1.54±0.3	1.18±0.4	1.37±0.5
		*	NS	NS	NS

Significance values refer to differences between sexes within each age group.
NS not significant; + $0.05<p<0.1$; * $p<0.05$.

(ii) Effects of varying spatial frequency

Evoked responses were recorded in young and old subjects to the onset of vertical sinusoidal grating patterns of 40% contrast and spatial frequencies 1, 2, 3, 5, 8, 10 and 15 c/deg.

Latency

In young subjects, the latencies of N1 and P1 were significantly positively correlated with spatial frequency. N2 and P2, on the other hand, showed no significant correlation with spatial frequency. Indeed, in the case of P2, there appeared to be a tendency towards shorter latencies at higher spatial frequencies (Fig. 36 and Table 15).

In old subjects, both N1 and P1 latency showed a significant positive correlation with spatial frequency. The latencies of N2 and P2 were not significantly correlated with spatial frequency. In fact, for the latter two components the relationship appeared to be diphasic (Fig. 37 and Table 15).

At each spatial frequency, the mean latency of each of the four VER components was numerically shorter in young subjects than it was in old subjects (Table 15). For N1 latency, the difference between age groups was significant at each of the spatial frequencies tested. The same was true of the P1 component with the exception of 2 c/deg and 15 c/deg where the difference was of marginal significance. For the N2 component, significant differences only occurred at 3, 5 and 8 c/deg, while at 10 c/deg the difference was of marginal significance. P2 latency showed no significant age-related changes at any of the spatial frequencies tested.

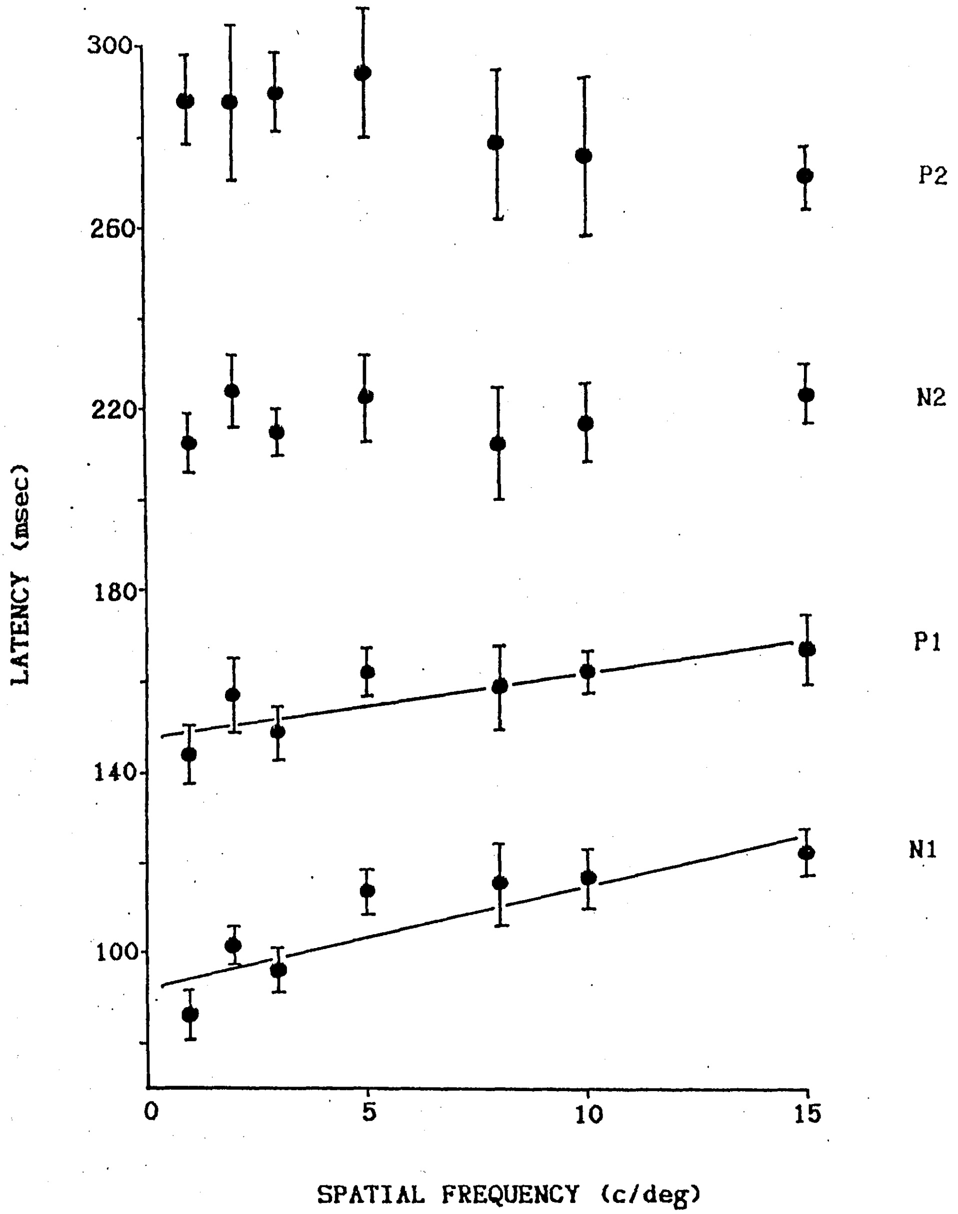


FIGURE 36. Effect of varying the spatial frequency of a 40% contrast grating pattern on the mean latency (± S.E.) of the components of the VER in young subjects.

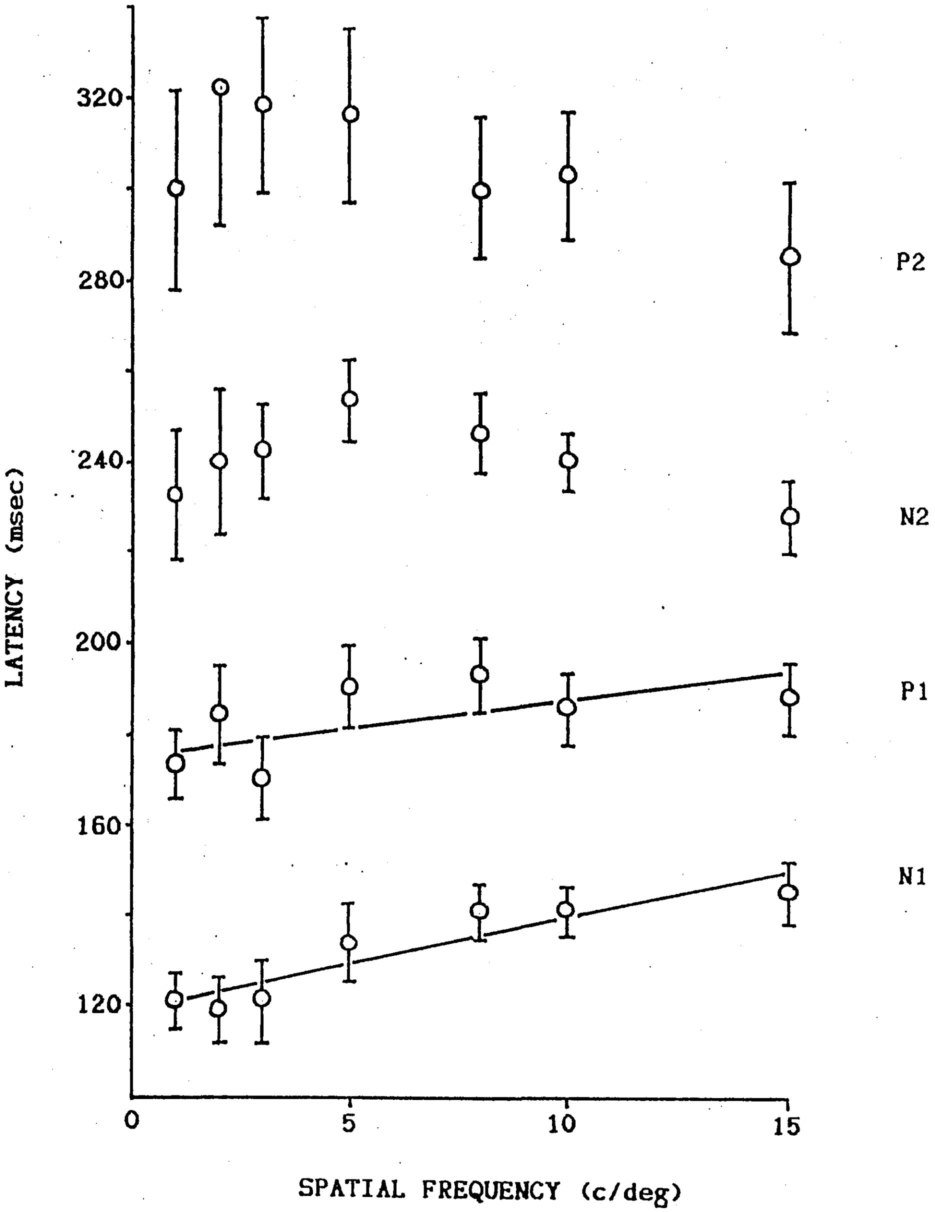


FIGURE 37. Effect of varying the spatial frequency of a 40% contrast grating pattern on the mean latency (± S.E.) of the components of the VER in old subjects.

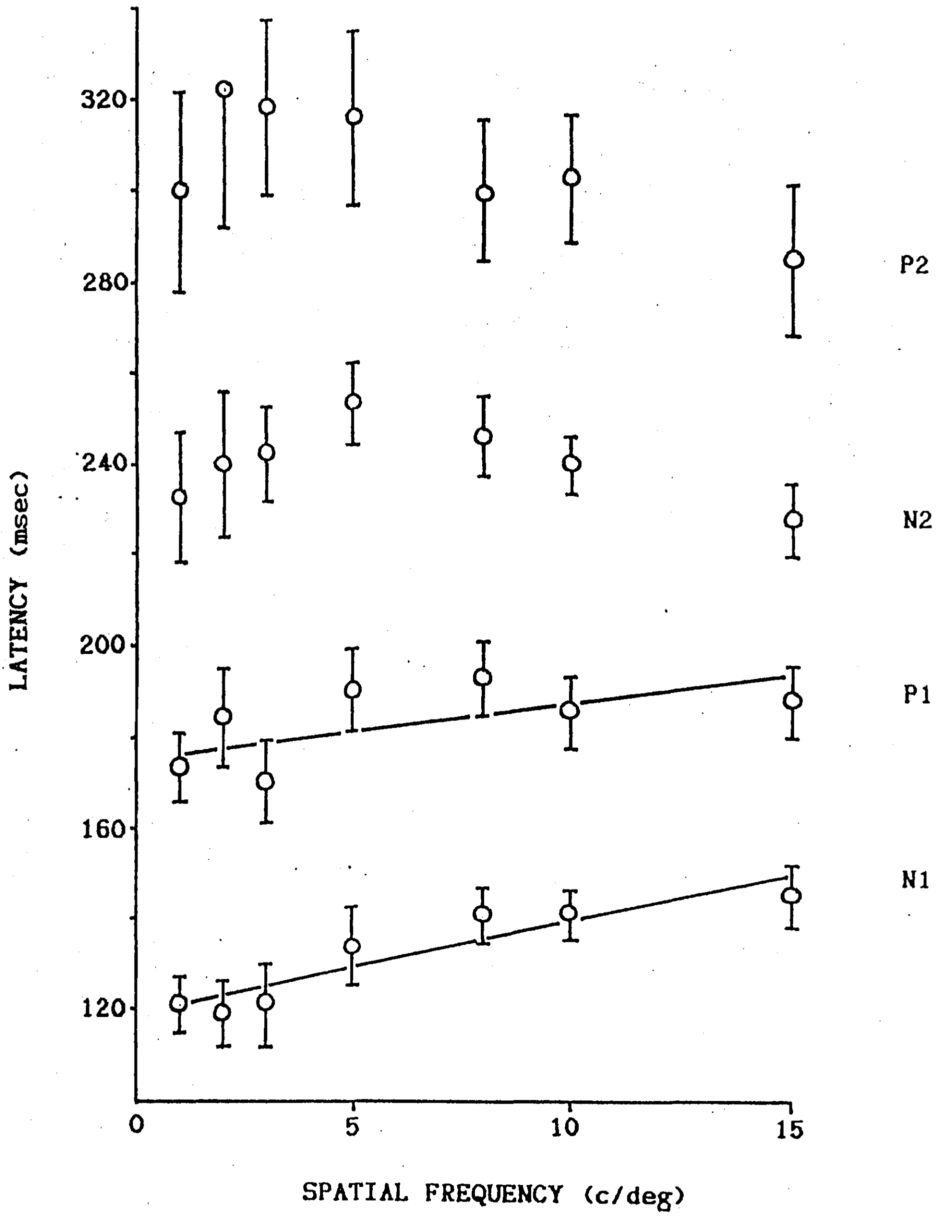


FIGURE 37. Effect of varying the spatial frequency of a 40% contrast grating pattern on the mean latency (± S.E.) of the components of the VER in old subjects.

TABLE 15 Dependence of PVER latency on spatial frequency at 40% contrast.

		SPATIAL FREQUENCY (c/deg)									
		1	2	3	5	8	10	15	$\overline{SE}$	*r*	*p*
N1	Young	87	102	97	114	116	117	123	*±5*	*0.39*	*<0.001*
	Old	121	119	121	134	141	142	146	*±7*	*0.42*	*<0.001*
		*	*	*	*	*	*	*			
P1	Young	144	158	150	163	159	163	168	*±6*	*0.40*	*<0.01*
	Old	173	185	171	191	194	187	189	*±8*	*0.25*	*=0.05*
		*	+	*	*	*	*	+			
N2	Young	213	224	215	223	213	218	224	*±8*	*0.00*	*>0.9*
	Old	232	240	243	254	247	241	229	*±10*	*-0.05*	*>0.7*
		NS	NS	*	*	*	+	NS			
P2	Young	289	288	290	295	279	277	273	*±13*	*-0.20*	*>0.1*
	Old	300	322	319	317	301	304	287	*±19*	*-0.17*	*>0.3*
		NS	NS	NS	NS	NS	NS	NS			

Table shows correlation coefficient (*r*) of latency (msec) against spatial frequency, and level of significance (*p*). Comparisons between young and old at each spatial frequency by *t*-test are also shown. NS not significant; + $0.05<p<0.1$; * $p<0.05$.

Statistical comparison of the corresponding regression equations of young and old subjects showed that there was no significant age-related difference in the slopes of the regression lines. Comparisons were also made of the intercepts of the regression lines at a point of reference common to both age groups: the mean stimulus spatial frequency for all subjects. For both N1 and P1 these intercepts were significantly different in young and old subjects (Table 16).

TABLE 16 Comparison of intercepts and slopes of regression equations of PVER latency against spatial frequency for young and old subjects.

		SLOPE	INTERCEPT
	YOUNG	+2.36	106.7
N1	OLD	+2.11	132.0
	p	*>0.25*	***<0.001***
	YOUNG	+1.47	156.5
P1	OLD	+1.32	183.1
	p	*>0.25*	***<0.001***

Rise time

In young subjects, the rise time of P1 and N2 was significantly inversely correlated with spatial frequency. On the other hand, rise time of N1 and P2 showed no significant correlation with spatial frequency. In the case of N1, there was the suggestion of a diphasic relationship (Fig. 38 and Table 17).

In old subjects, P1 and N2 rise time showed a significant inverse correlation with spatial frequency. N1 and P2 rise time showed no significant correlation with spatial frequency (Fig. 39 and Table 17).

There was a slight tendency for the mean rise time of N1 and P1 to be greater in old subjects than in young. In the case of N2 and P2 the magnitude of the mean rise times in the two groups was very similar. In fact, at only one spatial frequency, 1 c/deg, was rise time significantly different in young and old subjects, N1 rise time being shorter in the young group. At 3 c/deg, N1 rise time was marginally significantly longer in young subjects (Table 17).

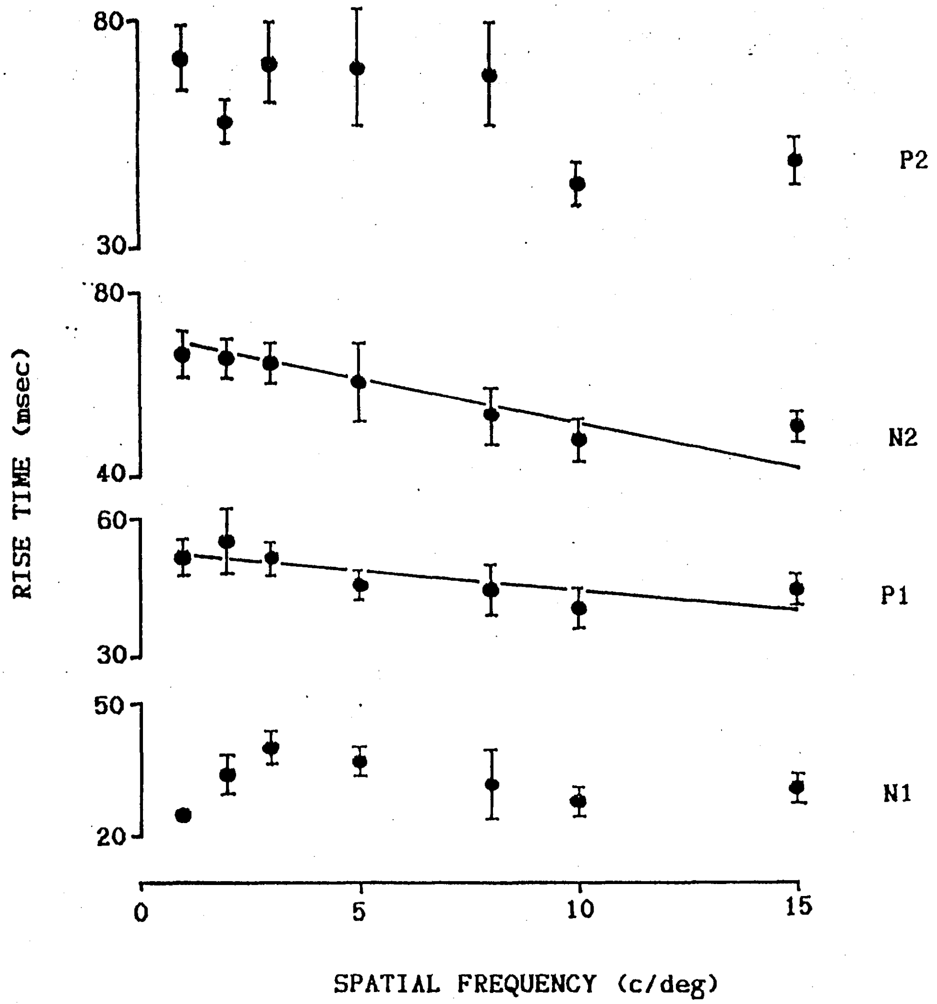


FIGURE 38. Effect of varying the spatial frequency of a 40% contrast grating pattern on the mean rise time (± S.E.) of the components of the VER in young subjects.

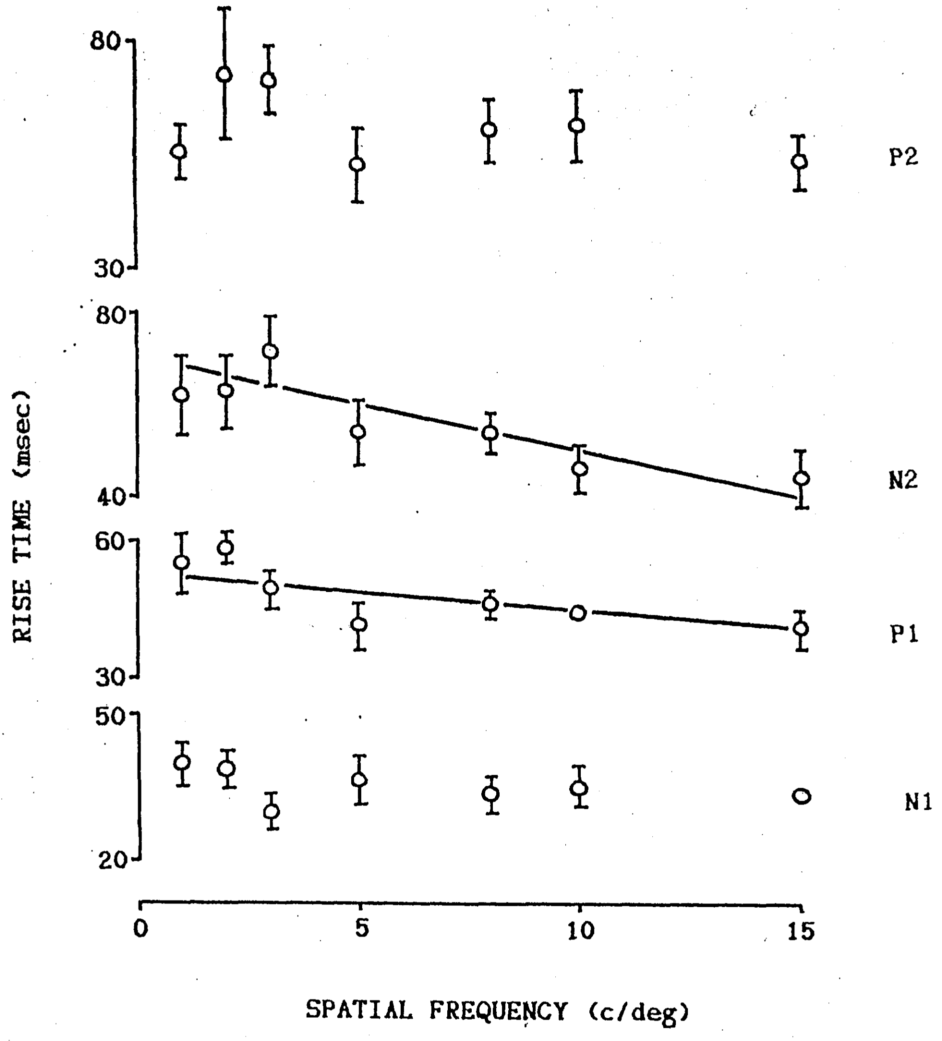


FIGURE 39. Effect of varying the spatial frequency of a 40% contrast grating pattern on the mean rise time (± S.E.) of the components of the VER in old subjects.

TABLE 17 Dependence of PVER rise time on spatial frequency at 40% contrast.

		SPATIAL FREQUENCY (c/deg)									
		1	2	3	5	8	10	15	$\overline{SE}$	*r*	*p*
	Young	25	34	40	37	32	28	31	*±4*	*−0.09*	*>0.5*
N1	Old	41	40	30	37	34	36	34	*±4*	*−0.10*	*>0.5*
		*	NS	+	NS	NS	NS	NS			
	Young	52	55	52	46	45	41	45	*±4*	*−0.30*	*<0.05*
P1	Old	55	59	49	41	46	44	41	*±4*	*−0.35*	*<0.01*
		NS	NS	NS	NS	NS	NS	NS			
	Young	67	66	65	61	53	48	51	*±5*	*−0.43*	*<0.01*
N2	Old	62	63	72	54	54	46	44	*±7*	*−0.38*	*<0.01*
		NS	NS	NS	NS	NS	NS	NS			
	Young	72	58	71	70	69	44	50	*±8*	*−0.13*	*>0.6*
P2	Old	56	73	72	53	61	62	59	*±8*	*−0.15*	*>0.6*
		NS	NS	NS	NS	NS	NS	NS			

Table shows correlation coefficient (*r*) of rise time (msec) against spatial frequency, and level of significance (*p*), Comparisons between young and old at each spatial frequency by *t*-test are also shown, NS not significant; + 0,05<p<0,1; * p<0,05, Statistical comparisons of the corresponding regression equations for P1 and N2 showed that there were no significant differences in the slopes of the regression lines of young and old subjects. Comparisons of the intercepts of the regression lines at the mean stimulus spatial frequency also revealed no significant differences between the two age groups (Table 18).

TABLE 18 Comparison of intercepts and slopes of regression equations of PVER rise time against spatial frequency for young and old subjects.

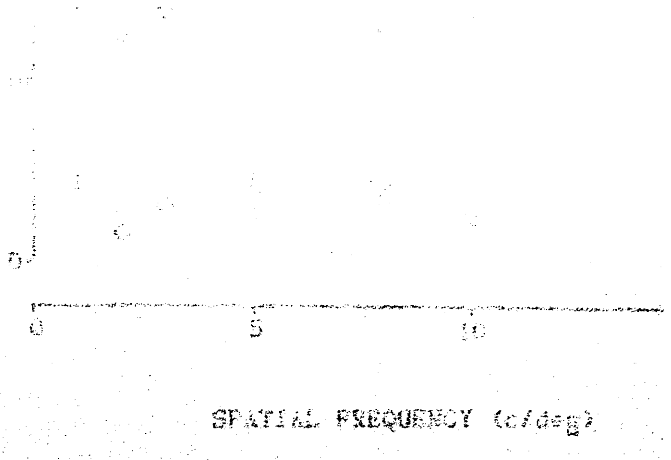
		SLOPE	INTERCEPT
P1	YOUNG	-0.87	48.3
	OLD	-1.01	48.0
	p	*>0.25*	*>0.25*
N2	YOUNG	-1.97	59.4
	OLD	-1.74	57.2
	p	*>0.25*	*>0.25*

Amplitude

In the young age group, both P1 and N2 amplitudes were significantly inversely correlated with spatial frequency. The amplitudes of N1 and P2 showed no significant correlation with spatial frequency (Fig. 40 and Table 19).

In the old group, the amplitudes of N1, P1, N2 and P2 were not significantly correlated with spatial frequency (Fig. 40 and Table 19).

Statistical comparison by t-test showed that there were no significant age-related differences in the amplitudes of N1 and P1. By inspection of the mean data for N2 and P2 it was clear that, in all cases, the mean amplitudes of these VER components were of a greater magnitude in young subjects than they were in old subjects (Table 19). However, in only two instances was the difference significant: at 10 c/deg both of these components were significantly larger in young subjects. In three instances, differences of marginal significance were present (Table 19).



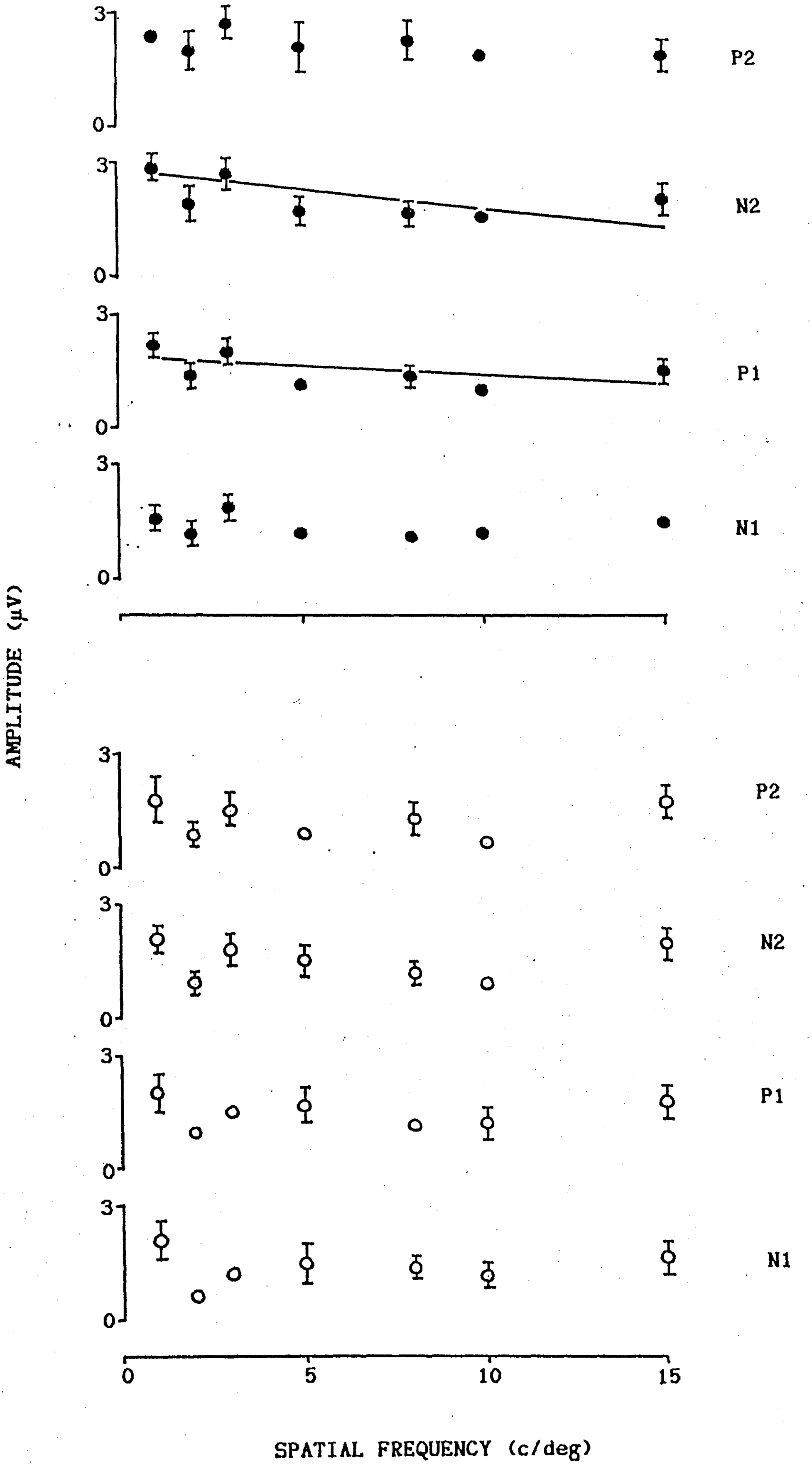


FIGURE 40. Effect of varying the spatial frequency of a 40% contrast grating pattern on the mean amplitude (± S.E.) of the components of the VER in young subjects (Top) and old subjects (Bottom).

TABLE 19 Dependence of PVER amplitude on spatial frequency at 40% contrast.

		SPATIAL FREQUENCY (c/deg)									
		1	2	3	5	8	10	15	$\overline{SE}$	r	p
N1	Young	1.58	1.17	1.87	1.21	1.09	1.17	1.46	*±.24*	*-0.09*	*>0.5*
	Old	2.14	0.59	1.24	1.47	1.38	1.14	1.65	*±.39*	*-0.10*	*>0.5*
		NS	NS	NS	NS	NS	NS	NS			
P1	Young	2.24	1.35	1.99	1.09	1.34	1.00	1.54	*±.26*	*-0.24*	*<0.05*
	Old	2.02	0.94	1.52	1.72	1.17	1.22	1.86	*±.32*	*-0.09*	*>0.5*
		NS	NS	NS	NS	NS	NS	NS			
N2	Young	2.86	1.92	2.74	1.73	1.68	1.56	2.05	*±.34*	*-0.32*	*<0.01*
	Old	2.04	0.91	1.77	1.52	1.18	0.88	1.96	*±.29*	*-0.08*	*>0.5*
		+	NS	+	NS	NS	*	NS			
P2	Young	2.38	2.01	2.75	2.11	2.29	1.91	1.89	*±.42*	*-0.15*	*>0.2*
	Old	1.83	0.90	1.54	0.94	1.32	0.72	1.77	*±.32*	*-0.08*	*>0.6*
		NS	NS	+	NS	NS	*	NS			

Table shows correlation coefficient (*r*) of amplitude (µV) against spatial frequency, and level of significance (*p*), Comparisons between young and old at each spatial frequency by *t*-test are also shown, NS not significant; + 0,05<p<0,1; * p<0,05,

2. PATTERN VER AND NORMALIZED CONTRAST

Contrast sensitivity was determined with an ascending method to sinusoidal grating patterns of 3 and 8 c/deg.

At 3 c/deg, contrast sensitivity was significantly lower in old subjects compared with young subjects ($p<0.001$). Mean log contrast sensitivity in the young group was 2.12 (SE ±0.04) while in the old group it was 1.48 ±0.07. At 8 c/deg, old subjects again had the significantly lower contrast sensitivity of the two groups ($p<0.001$). In the young subjects the mean contrast sensitivity was 1.92 ±0.04 compared with a value of 0.92 ±0.11 in the old subjects (Fig. 41). Within each age-group, no significant differences were found between male and female subjects ($p>0.1$).

PVERs were recorded to the onset of vertical sinusoidal grating patterns at the above spatial frequencies and over a range of contrasts which were multiples of the individual's threshold. Hence, stimuli were 'normalized' with respect to the subject's contrast sensitivity. The use of lower-field stimulation resulted in a PVER which generally contained the same components as the responses in the previous section where full-field stimulation was employed. However, amplitudes were somewhat greater and there was some accentuation of P1 while P2 was less frequently observed (Fig. 42 and *cf* Fig. 32). Typical records are shown in Figure 43 in which can be seen the effects of a range of normalized contrasts on the PVER of one subject. The most obvious change is an increase in component latency as contrast is reduced, while amplitude and rise time are little affected.

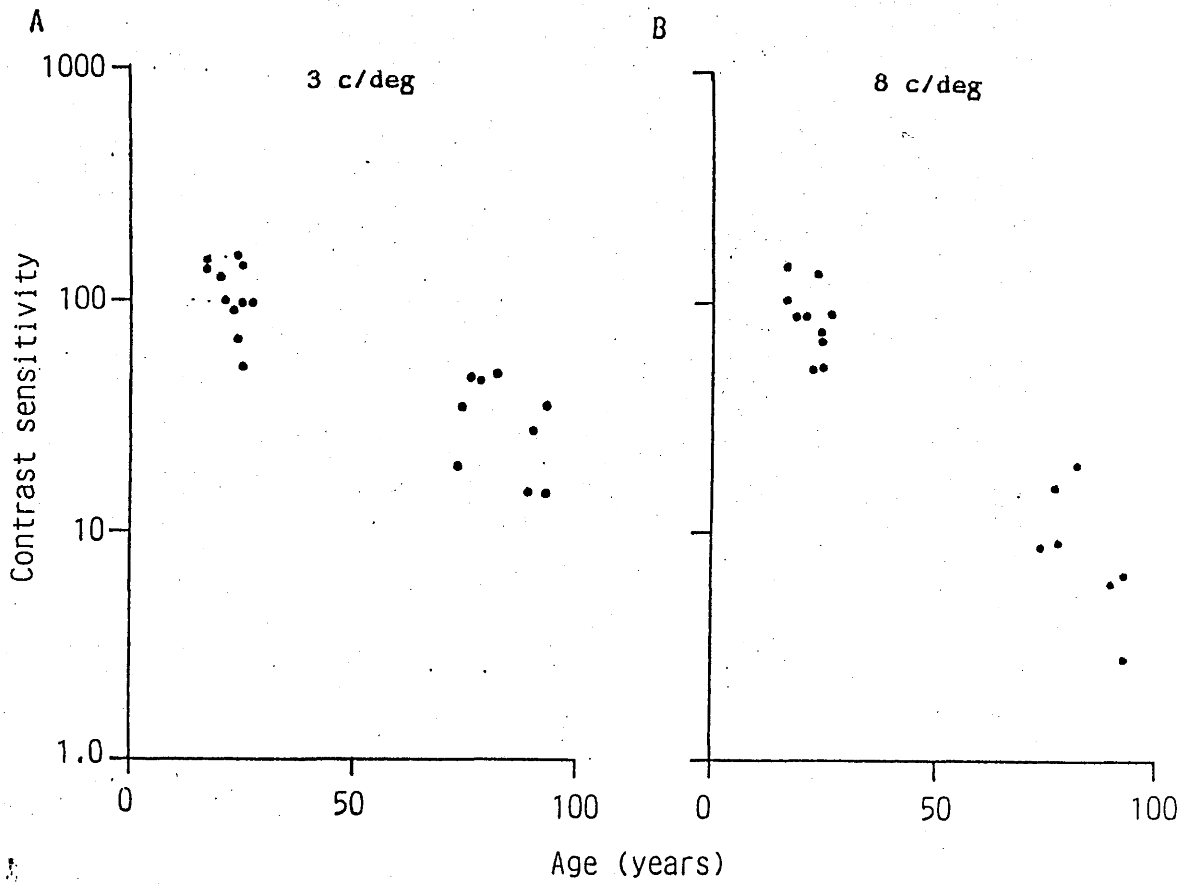


FIGURE 41. Contrast sensitivity (logarithmic units) determined by the ascending method for 3 c/deg (A) and 8 c/deg (B) at different ages.

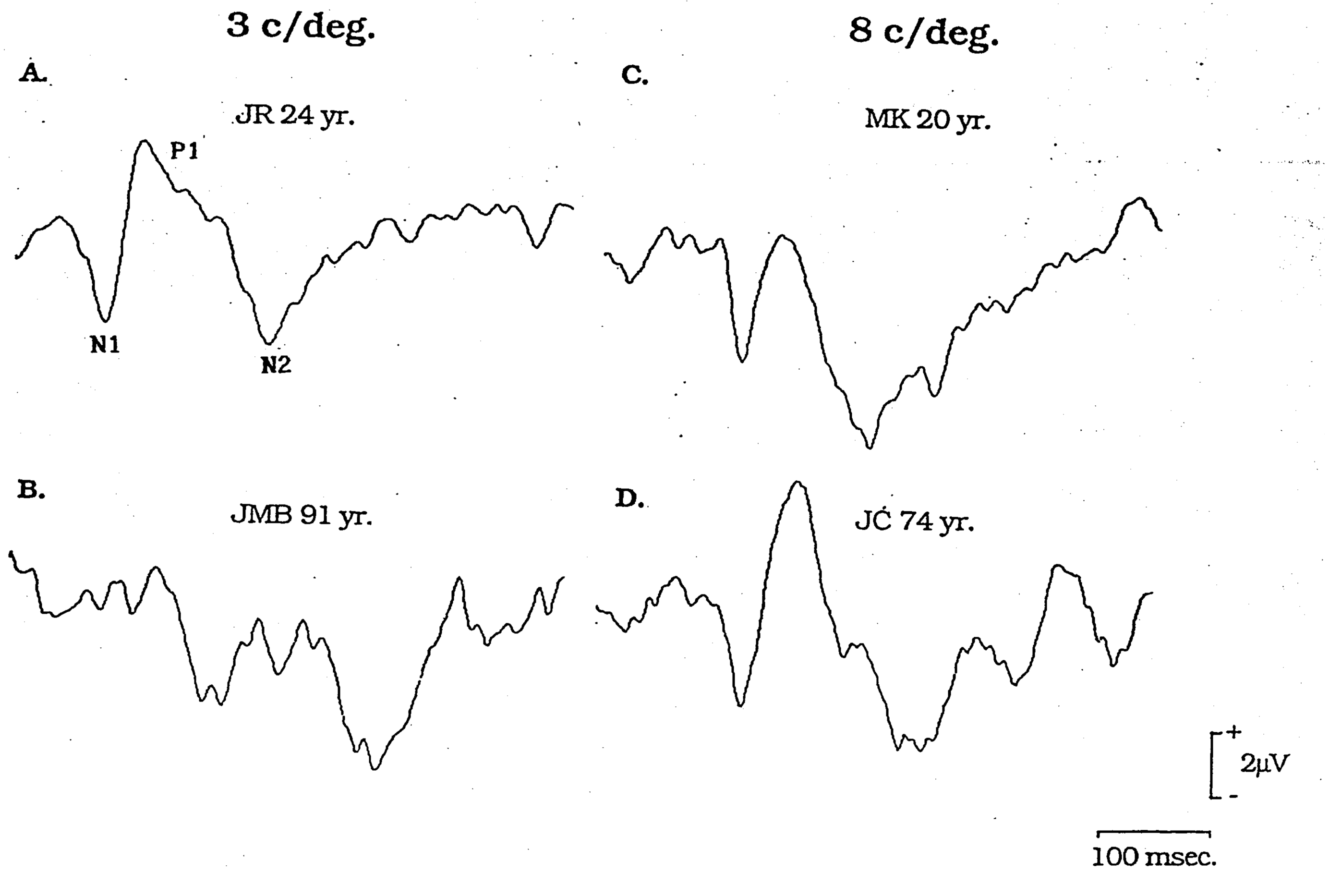


FIGURE 42. Typical VERs in young and old subjects to grating pattern onset. (A & B) PVER elicited by 3 c/deg pattern at 20x contrast threshold; (C & D) PVER elicited by 8 c/deg pattern at 10x contrast threshold.

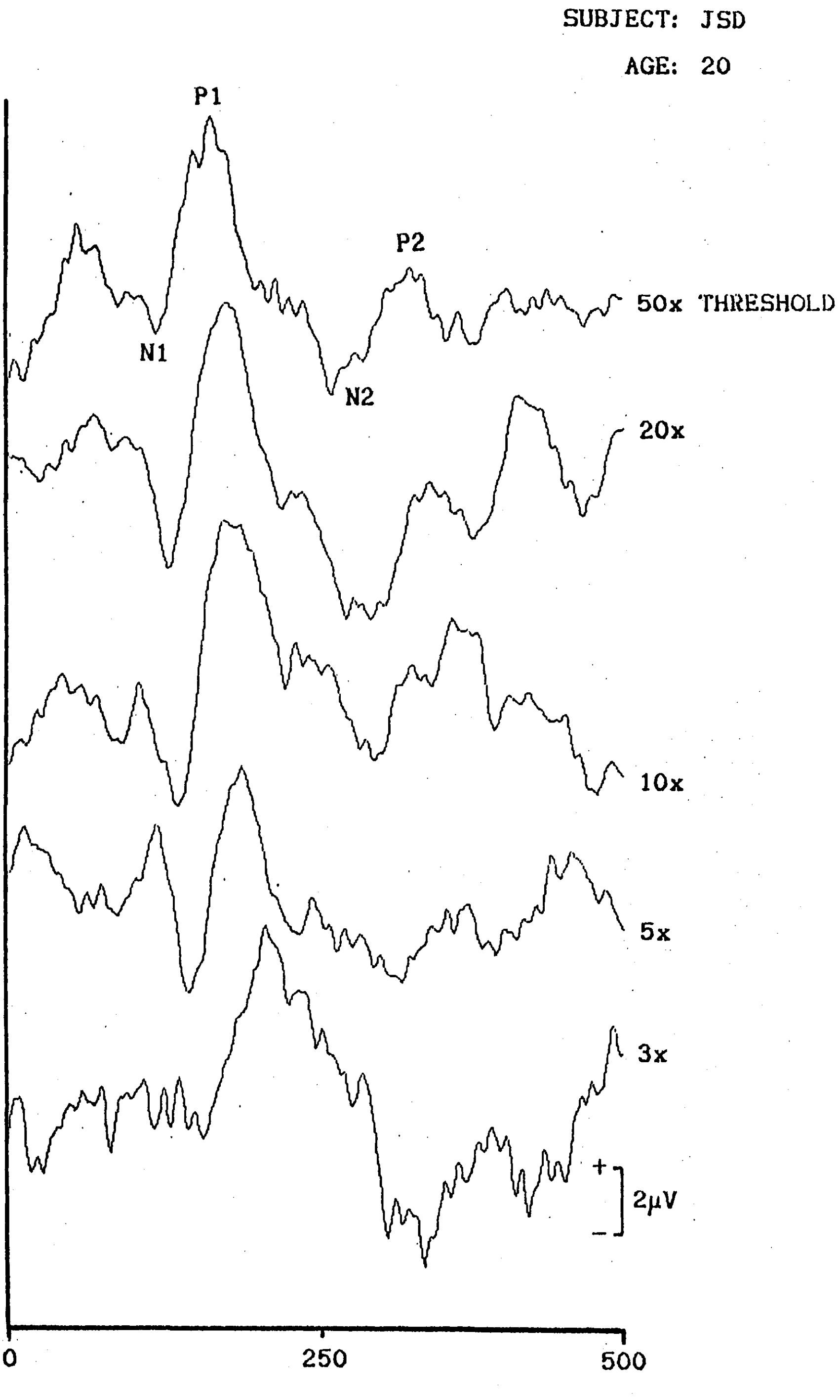


FIGURE 43. Effect of varying contrast relative to threshold on the VER to onset of a 3 c/deg grating pattern.

A comparison of male and female subjects could only be carried out for young subjects. This was done at 20x contrast threshold for both 3 and 8 c/deg. No significant sex differences were found for latency, rise time or amplitude ($p>0.1$). Hence, male and female data were combined and analysed collectively.

Latency

In order to determine the best relationship between latency and normalized contrast the following regression analyses were carried out: latency against normalized contrast; latency against log normalized contrast; log latency against log normalized contrast; latency^{-1} against normalized contrast; latency^{-1} against log normalized contrast. Generally, the more significant correlation was found when linear latency was regressed against log normalized contrast.

3 c/deg

In young subjects, there was a significant inverse correlation between log normalized contrast and the latencies of N1, P1, N2 and P2 ($r= -0.40$ to -0.72; $p< 0.05$ in all cases) (Fig. 44).

In old subjects, a similar significant correlation was present between log normalized contrast and the latencies of N1, P1 and N2 ($r= -0.39$ to -0.56; $p<0.05$ in all cases). The relationship of P2 latency to log normalized contrast was of marginal significance ($r= -0.49$; $0.05<p<0.1$) (Fig. 44).

3 c/deg.

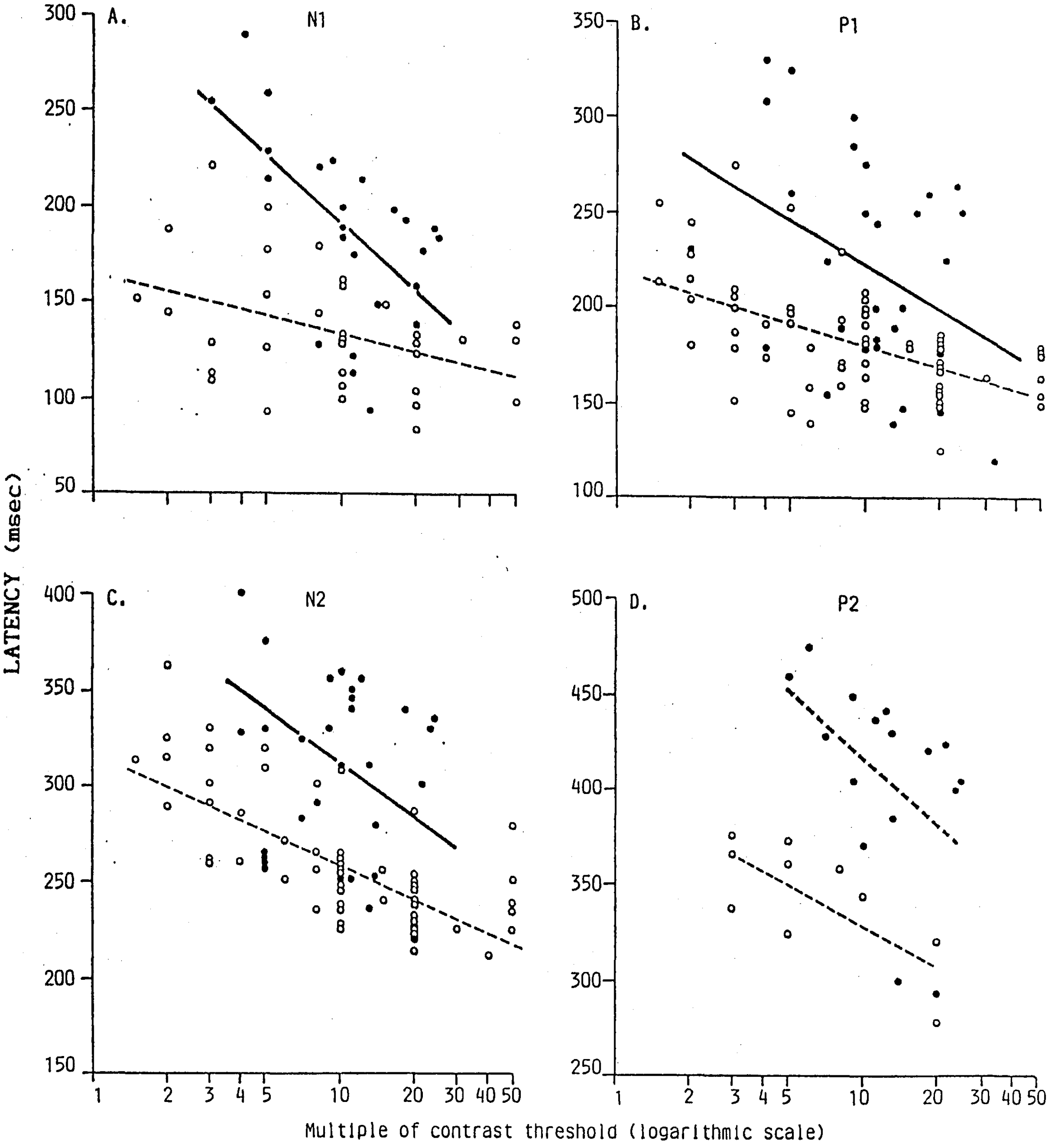


FIGURE 44. Effect of varying the contrast relative to threshold of a 3 c/deg grating pattern on the latency of N1, P1, N2 and P2 components of transient PVER. Young subjects are shown by unfilled circles, with corresponding regression equation represented by dashed line; old subjects are shown by filled circles, with corresponding regression equation by solid line and regression equation of marginal significance by heavy dashed line.

The corresponding regression equations of young and old subjects were statistically compared. Intercepts with the line drawn at the mean stimulus contrast were found to be significantly different between young and old subjects for N1, P1, N2 and P2 (Table 20). Visual inspection of the regression lines of latency against log normalized contrast suggested that the slopes were somewhat steeper in old subjects as compared with young subjects. However, a statistical comparison showed that the slopes of N1, P1, N2 and P2 were not significantly different between the two age groups (Table 20).

TABLE 20 Comparison of intercepts and slopes of regression equations of PVER latency against log normalized contrast at 3 c/deg for young and old subjects.

INTERCEPTS

	N1	P1	N2	P2
YOUNG	136	182	261	335
OLD	192	224	312	423
	<0.001	*<0.001*	*<0.001*	*<0.05*

SLOPES

	N1	P1	N2	P2
YOUNG	-30.7	-38.4	-57.2	-67.4
OLD	-117	-79.6	-91.6	-119
	>0.25	*>0.25*	*>0.25*	*>0.25*

The differences in intercepts between age groups were confirmed by *t*-tests at certain contrast multiples. A comparison was made between young subjects at 20x threshold and old subjects at 18-23x threshold. It was necessary to pool the data from the old subjects due to the shortage of points at 20x threshold, although each old subject was included only once within that range. The data from old subjects between 8-12x threshold were also pooled and statistically compared with the young group at 10x threshold.

At both 10x and 20x threshold, the mean latency values for N1, P1 and N2 were significantly greater in old subjects compared with young subjects (Table 21 and *cf* Figs. 42A and B). The small number of data points for P2 precluded statistical analysis.

TABLE 21 Mean latencies (msec) of components of PVER elicited by 3 c/deg grating pattern at 20X and 10x contrast threshold.

20x THRESHOLD

	N1	P1	N2	P2
Young	113 ±8	165 ±5	240 ±5	-
Old	181 ±9	226 ±7	293 ±22	-
p	***<0.001***	***<0.001***	***<0.01***	

10x THRESHOLD

	N1	P1	N2	P2
Young	130 ±8	182 ±6	251 ±6	-
Old	168 ±12	218 ±15	307 ±9	-
p	***<0.05***	***<0.05***	***<0.001***	

Significance values refer to differences between young and old groups,

8 c/deg

In young subjects, the latencies of N1, P1, N2 and P2 were significantly inversely related to log normalized contrast ($r= -0.57$ to -0.86; $p<0.01$ in all cases) (Fig. 45).

In old subjects, no significant correlations were found between log normalized contrast and the latencies of N1, P1 and N2 ($p>0.5$ in all cases). However, by inspection of the data it was apparent that, in the case of both P1 and N2, the presence of an outlying point may have been biasing the analysis (Fig. 45). When these points were omitted, the relationship of P1 and N2 latency to log normalized contrast was found to be significant ($r= -0.64$ and -0.61 respectively; $p<0.05$ in both cases). P2 latency was marginally significantly correlated with log normalized contrast, becoming shorter as contrast was increased ($r= -0.66$; $0.05<p<0.1$) (Fig. 45).

Statistical comparisons were made of the regression equations of P1, N2 and P2 latency against log normalized contrast for young and old subjects. For P1 and N2, intercepts were compared at 5x threshold, while for P2 the comparison was made at 8x threshold (where overlap between the two groups of data was at a maximum). No significant differences were found between young and old subjects (Table 22).

Similarly, a statistical comparison of the corresponding regression equations revealed no significant differences in the slopes of the regression lines in the two age groups (Table 22).

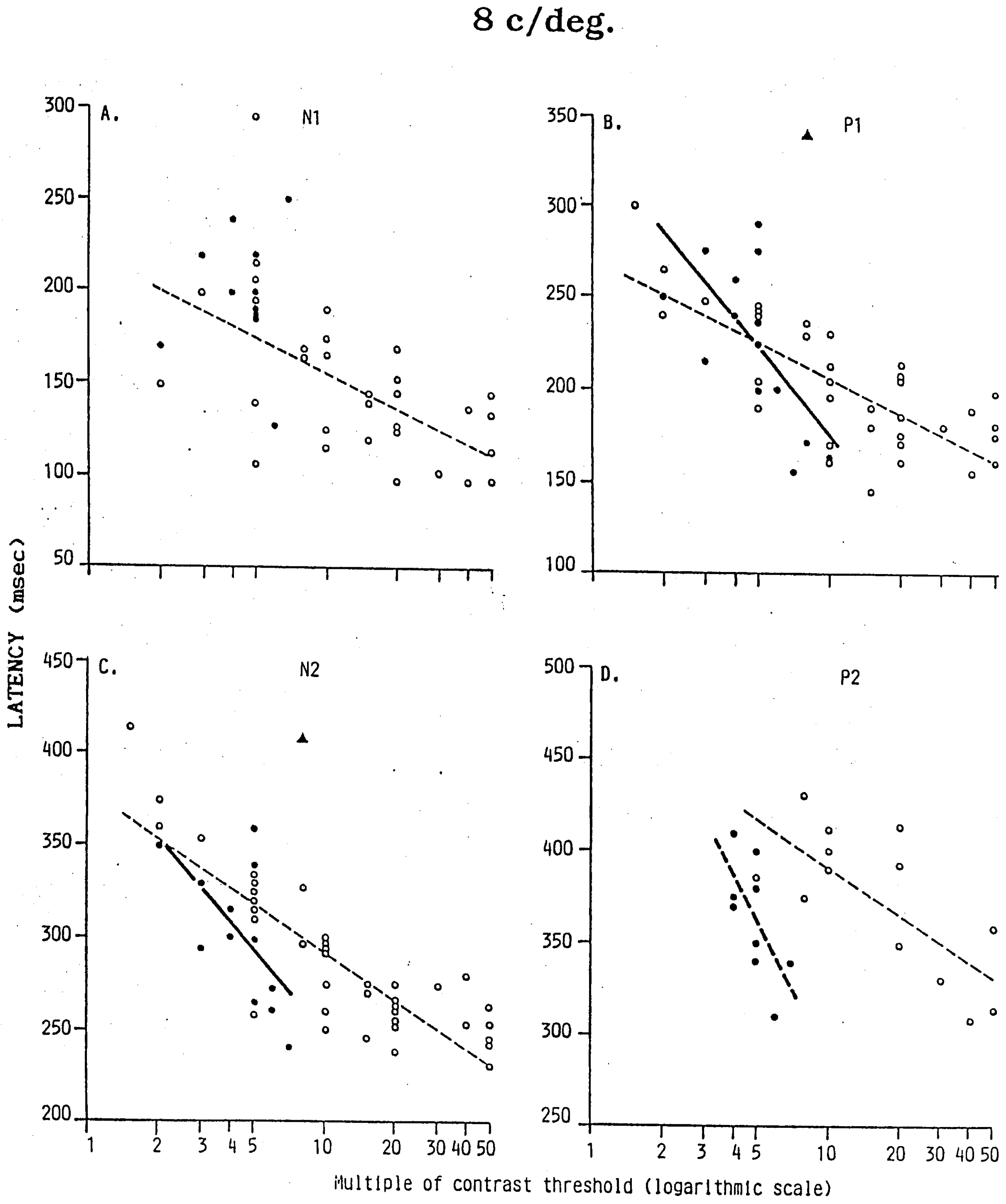


FIGURE 45. Effect of varying the contrast relative to threshold of an 8 c/deg grating pattern on the latency of N1, P1, N2 and P2 components of transient PVER. Young subjects are shown by unfilled circles, with corresponding regression equation represented by dashed line; old subjects are shown by filled circles, with corresponding regression equation by solid line and regression equation of marginal significance by heavy dashed line. Filled triangles represent outlying points of old subjects which were omitted from the regression analysis.

TABLE 22 Comparison of intercepts and slopes of regression equations of latency against log normalized contrast at 8 c/deg for young and old subjects.

INTERCEPTS

	P1	N2	P2
YOUNG	227	321	405
OLD	225	295	318
	>0.25	*>0.25*	*>0.25*

SLOPES

	P1	N2	P2
YOUNG	-64.6	-86.1	-86.1
OLD	-156.8	-149.8	-251.2
	>0.25	*>0.25*	*>0.1*

By visual inspection of the data it was not possible to identify any obvious differences between the latencies of the two age groups. For the purposes of statistical analysis by t-test, the data between 4x and 6x threshold in old subjects were combined into a single '5x threshold' category. This was then compared with the 5x threshold data in young subjects. At P2, the insufficient number of data points precluded statistical analysis. For N1, P1 and N2 there were no significant differences between the latencies of young and old subjects (Table 23 and *cf* Figs. 42C and D).

TABLE 23 Mean latencies (msec) of components of PVER elicited by 8 c/deg grating pattern at 5x contrast threshold.

	LATENCY (msec)			
	N1	P1	N2	P2
Young	211 ±24	225 ±17	313 ±10	-
Old	190 ±13	238 ±12	306 ±14	-
p	*>0.5*	*>0.5*	*>0.6*	

Significance values refer to differences between young and old groups.

Comparison of regression equations for 3 and 8 c/deg

Within young and old groups the regression equations of latency against log normalized contrast at 3 c/deg were compared with those at 8 c/deg. In both young and old subjects there were no significant differences in the slopes of the corresponding lines ($p>0.25$ in all cases). In old subjects, the intercepts were not significantly different at the two spatial frequencies ($p>0.25$ in all cases). In young subjects the differences in intercept at 3 and 8 c/deg were significant for P1, N2 and P2, being higher for 8 c/deg ($p<0.05$ in all cases). The difference in the N1 intercepts was of marginal significance ($0.05<p<0.1$).

Rise time

The best correlation was between rise time and log normalized contrast.

3 c/deg

In young subjects, the rise times of N1, P1 and N2 were found to be significantly correlated with log normalized contrast ($r \geqslant -0.31$; $p<0.05$ in all cases). P2 rise time, on the other hand, showed no significant correlation with log normalized contrast ($r= -0.06$; $p>0.5$) (Fig. 46).

In the old subjects, rise times of N1, P1, N2 and P2 showed no significant correlation with log normalized contrast ($r= -0.23$ to $+0.06$; $p>0.2$ in all cases) (Fig. 46).

For the purposes of statistical analysis there was the same pooling of data in old subjects as was carried out for latencies.

At 20x threshold, N1 rise time was longer in old subjects though the difference was only of marginal significance ($0.05<p<0.1$). For N2, the situation was reversed, mean rise time being longer in young subjects; again the difference was only of marginal significance ($0.05<p<0.1$). For P1, there were no significant differences between the latencies of the two groups ($p>0.6$), while for P2 rise time an insufficient number of data points precluded analysis (Table 24).

At 10x threshold there were no significant age-related differences in rise time for N1, P1 or N2 ($p>0.6$) (Table 24).

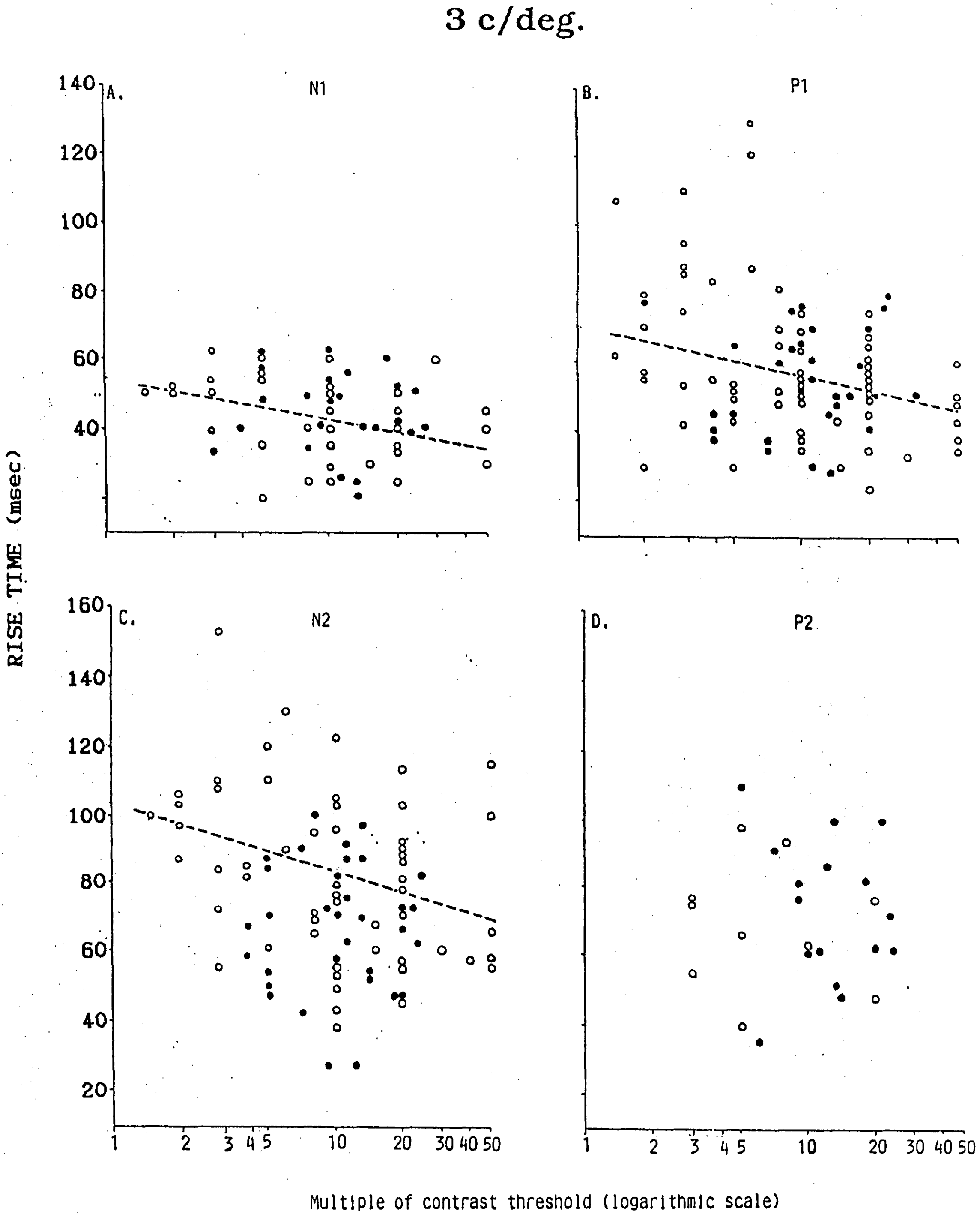


FIGURE 46. Effect of varying the contrast relative to threshold of a 3 c/deg grating pattern on the rise time of N1, P1, N2 and P2 components of transient PVER. Young subjects are shown by unfilled circles, with corresponding regression equation represented by dashed line; old subjects are shown by filled circles.

TABLE 24 Mean rise times (msec) of components of PVER elicited by 3 c/deg grating pattern at 20x and 10x contrast threshold.

20x THRESHOLD

	N1	P1	N2	P2
Young	37 ±4	54 ±4	80 ±6	-
Old	47 ±3	57 ±6	63 ±6	-
p	$0.05<p<0.1$	>0.6	$0.05<p<0.1$	

10x THRESHOLD

	N1	P1	N2	P2
Young	45 ±5	51 ±4	74 ±9	-
Old	38 ±5	57 ±5	72 ±6	-
p	>0.6	>0.6	>0.8	

Significance values refer to difference between young and old groups,

8 c/deg

In young subjects, the correlation of N1 and P1 rise time with log normalized contrast was of marginal significance (r= -0.31; 0.05<p<0.1) (Fig. 47). N2 rise time *was* significantly correlated with log normalized contrast (r= -0.53; p<0.01) (Fig. 47). P2 rise time, however, showed no significant correlation with log normalized contrast (r= -0.11; p>0.1) (Fig. 47).

In the old group, there was no significant correlation between stimulus contrast and rise time of N1, P1, N2 and P2 (r= -0.28 to +0.03; p>0.5 in all cases) (Fig. 47).

The data between 4-6x threshold in old subjects was compared with that at 5x threshold in young subjects. In only one instance was rise time significantly different between the two age-groups: N2 rise time was longer in young than in old subjects. For both N1 and P1 the differences between age groups were not significant (Table 25).

TABLE 25 Mean rise times (msec) of components of PVER elicited by 8 c/deg grating pattern at 5x contrast threshold.

	RISE TIME (msec)			
	N1	P1	N2	P2
Young	63 ±7	47 ±7	83 ±7	-
Old	46 ±7	46 ±5	52 ±3	-
p	*>0.1*	*>0.8*	***<0.05***	

Significance values refer to differences between young and old groups.

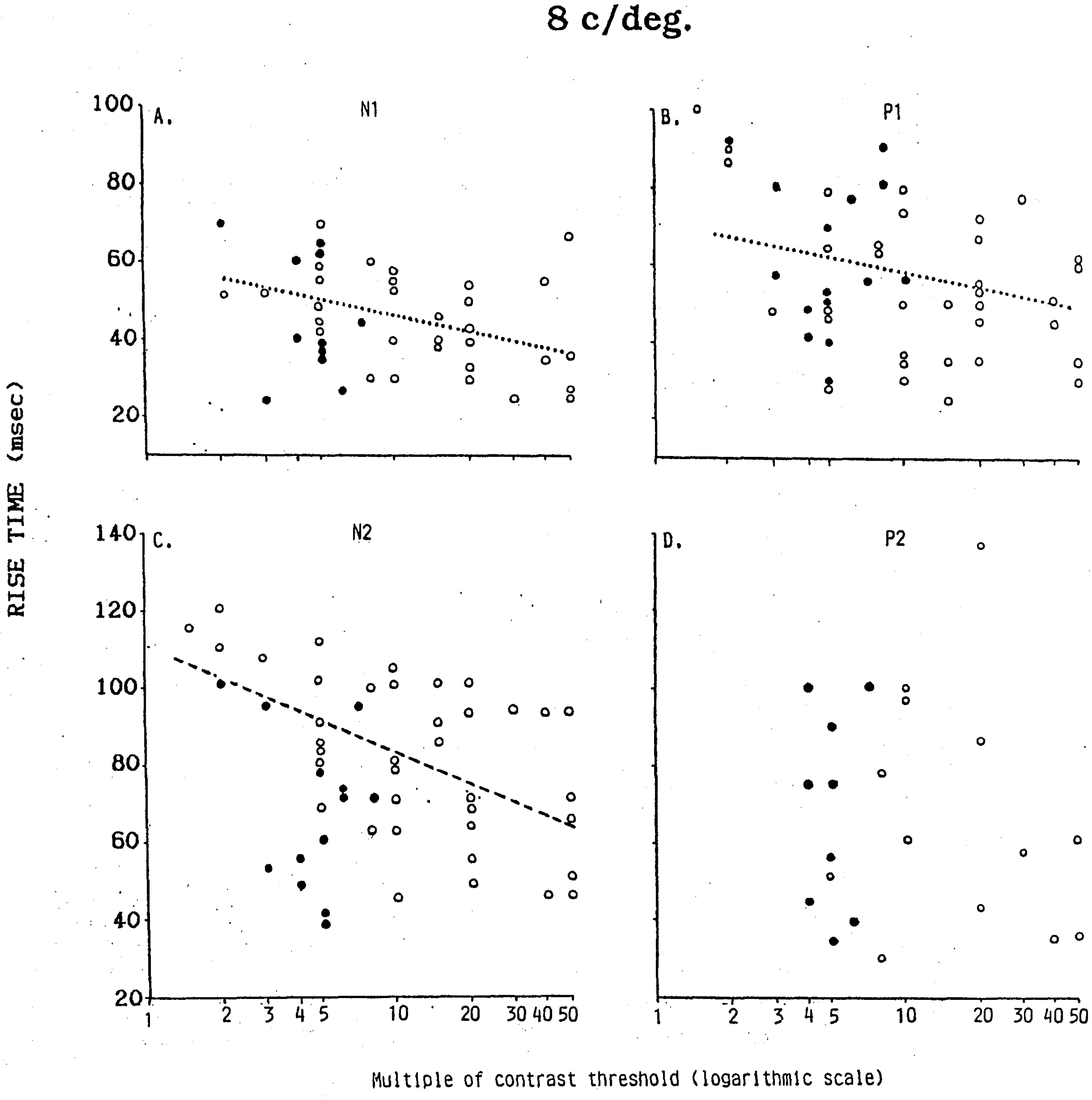


FIGURE 47. Effect of varying the contrast relative to threshold of an 8 c/deg grating pattern on the rise time of N1, P1, N2 and P2 components of transient PVER. Young subjects are shown by unfilled circles, with corresponding regression equation represented by dashed line and regression equations of marginal significance by dotted line; old subjects are shown by filled circles.

Amplitude

3 c/deg

In both young and old subjects, no significant correlation was found between normalized contrast and the amplitudes of N1, P1, N2 and P2 (Fig. 48). This was irrespective of whether the contrast was expressed in linear or logarithmic units ($r = -0.23$ to $+0.33$; $p > 0.1$ in all cases).

Data from 18-23x threshold in old subjects were compared by *t*-test with data at 20x threshold in young subjects; data from 8-12x threshold in old subjects were compared with that at 10x threshold in the young group. Mean amplitudes were numerically larger in young subjects in all but one instance, N1 at 20x threshold, where old subjects had the higher mean amplitude. The differences were significant only for N2 at 10x and 20x threshold (Table 26). A difference of marginal significance was present for P1 at 10x threshold.

3 c/deg.

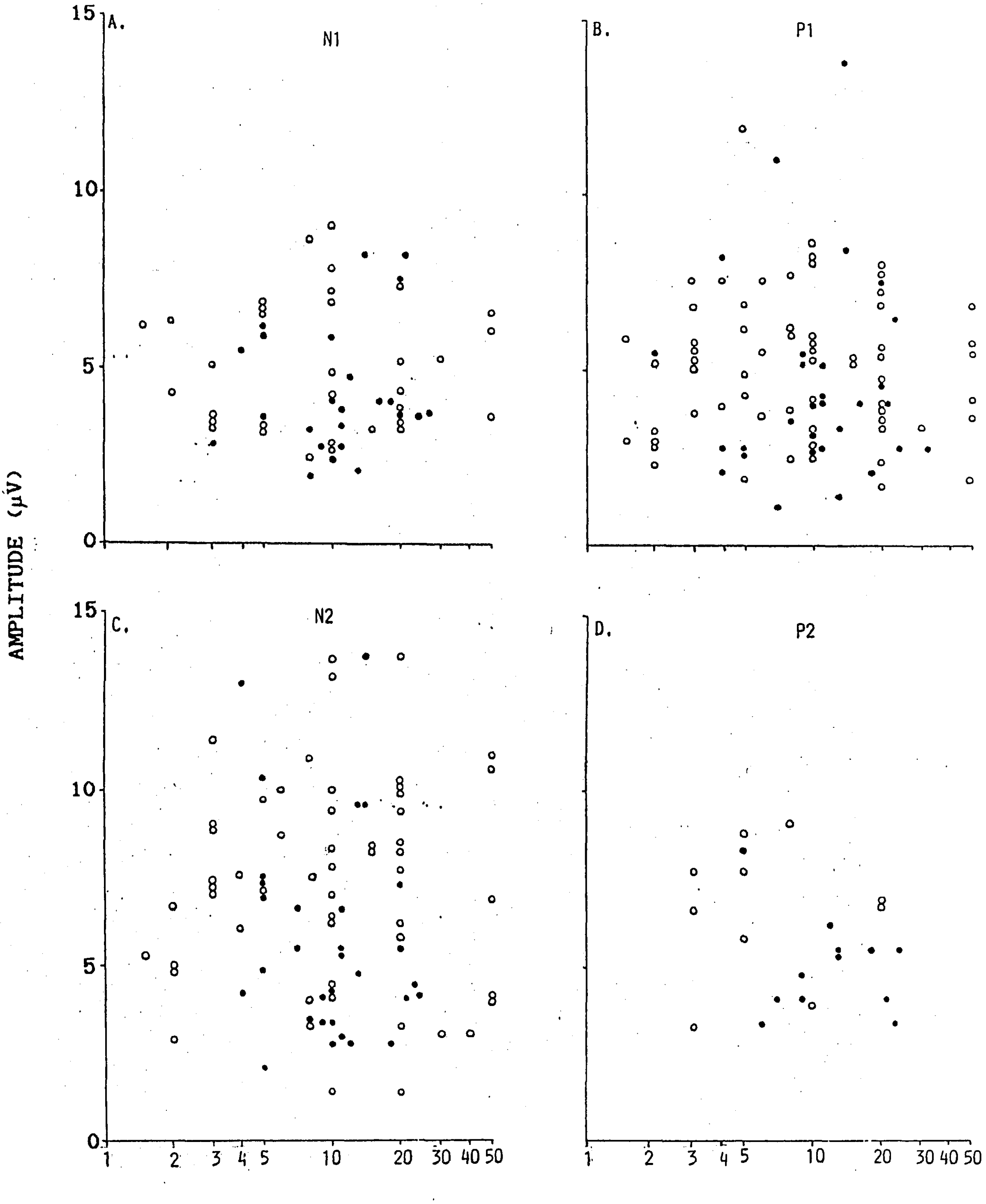


FIGURE 48. Effect of varying the contrast relative to threshold of a 3 c/deg grating pattern on the amplitude of N1, P1, N2 and P2 components of transient PVER. Young subjects are shown by unfilled circles; old subjects are shown by filled circles.

TABLE 26 Mean amplitudes (µV) of components of PVER elicited by 3 c/deg grating pattern at 20x and 10x contrast threshold.

20x THRESHOLD

	N1	P1	N2	P2
Young	4.74 ±0.75	5.10 ±0.67	7.88 ±0.96	-
Old	5.43 ±0.80	4.56 ±0.72	3.69 ±0.63	-
p	*>0.5*	*>0.6*	***<0.05***	

10x THRESHOLD

	N1	P1	N2	P2
Young	5.53 ±0.94	5.54 ±0.72	7.66 ±1.04	-
Old	3.78 ±0.36	3.77 ±0.33	4.54 ±0.54	-
p	*>0.1*	*0.05<p<0.1*	***<0.05***	

Significance values refer to differences between young and old groups,

8 c/deg

In young subjects, a marginally significant correlation was present between N1 amplitude and log normalized contrast (r= 0.38; $0.05<p<0.1$) although not with linear normalized contrast (r= 0.33; $p>0.1$). For P1, N2 and P2, there was no significant correlation between amplitude and either linear or log normalized contrast (r= -0.24 to +0.34; $p>0.1$ in all cases) (Fig 49).

8 c/deg.

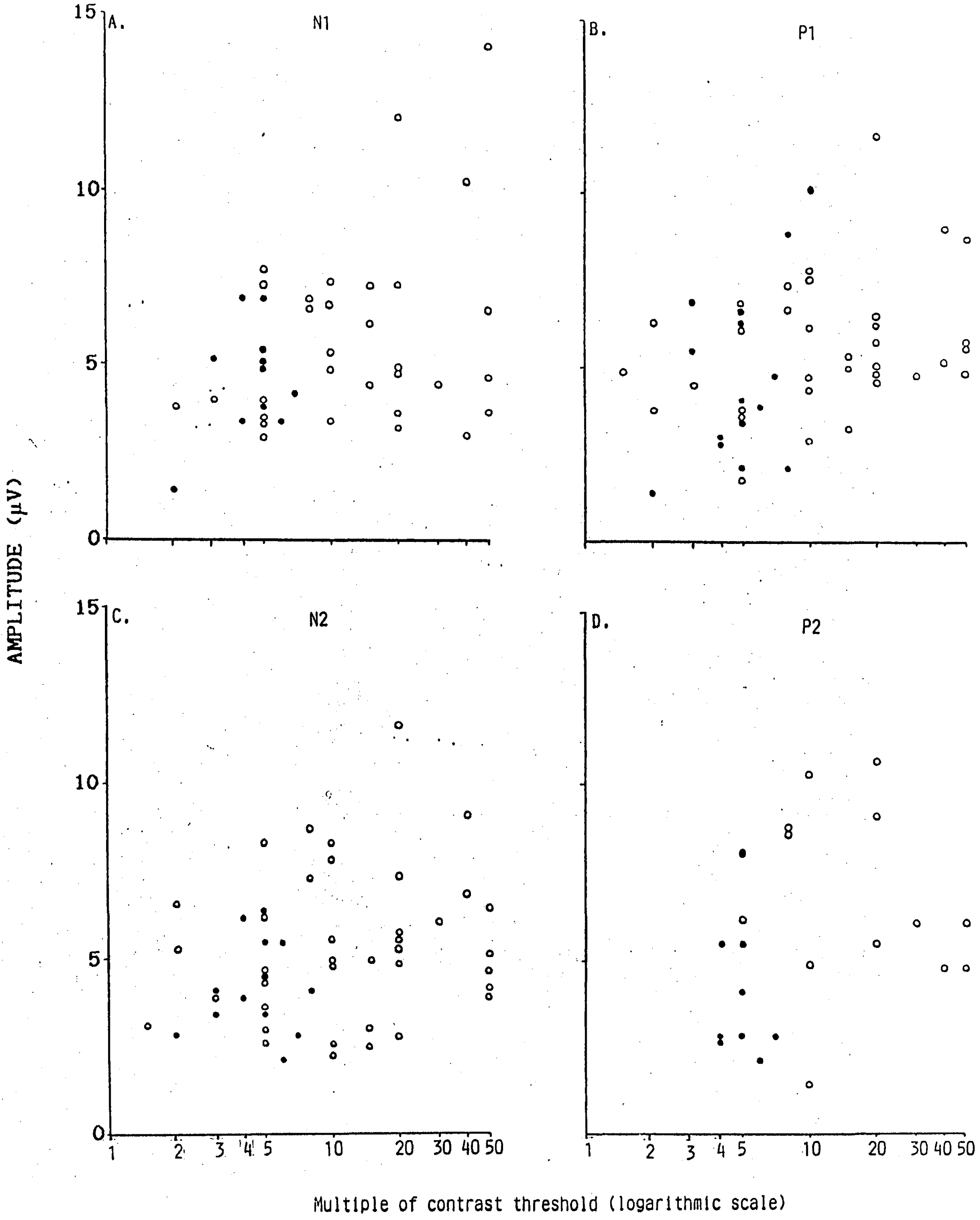


FIGURE 49. Effect of varying the contrast relative to threshold of an 8 c/deg grating pattern on the amplitude of N1, P1, N2 and P2 components of transient PVER. Young subjects are shown by unfilled circles; old subjects are shown by filled circles.

In the old subjects, no significant correlations were found between normalized contrast and the amplitudes of N1, P1, N2 and P2 (r= -0.38 to +0.37; p>0.1 in all cases) (Fig. 49).

Data from 4-6x threshold in old subjects were pooled and compared with data at 5x threshold in young subjects. For N1, P1, N2 and P2 there were no significant differences between the amplitudes of young and old subjects (p>0.2 in all instances) (Table 27).

TABLE 27 Mean amplitudes (μV) of components of PVER elicited by 8 c/deg grating pattern at 5x contrast threshold.

	AMPLITUDE (μV)			
	N1	P1	N2	P2
Young	3.40 ±0.23	5.18 ±0.90	5.85 ±0.92	-
Old	4.55 ±0.75	4.01 ±0.88	4.57 ±0.50	-
p	*>0.2*	*>0.5*	*>0.2*	

Significance values refer to differences between young and old groups.

Full-field vs hemi-field stimulation

The waveforms evoked by lower hemi-field stimulation (Section 2) were similar in shape to those evoked by full-field stimulation (Section 1) although the P1 component appeared to be somewhat accentuated by lower-field stimulation, while the P2 component was less often present. Inspection of the data suggested that there was a tendency for the components to have larger amplitudes and longer latencies and rise times when hemi-field stimulation was used. Statistical verification of this observation was problematic due to the differing modes of stimulus presentation (i.e. physical contrast versus normalized contrast). However, in young subjects at 3 c/deg, a statistical comparison was made of the above variables at 20% contrast full-field stimulation and 20x threshold lower-field stimulation. In the latter case, the mean grating pattern contrast was 17%. It was found that, for N1, P1 and N2, mean amplitudes were significantly higher when hemi-field stimulation was used ($p<0.05$ in all cases), while rise times for N1 and latencies for P1 were significantly longer (Table 28). The small number of points for the P2 component precluded statistical analysis.

TABLE 28 Mean latencies, rise times and amplitudes (± S.E) of components of VER elicited by a 3 c/deg grating pattern presented at 20% contrast full-field stimulation and a mean of 17% contrast lower hemi-field stimulation.

LATENCY (msec)

	N1	P1	N2	P2
Full-field	101 ±5	146 ±5	221 ±9	-
Hemi-field	113 ±8	165 ±5	240 ±6	-
p	*>0.2*	*<0.05*	*>0.1*	

RISE TIME (msec)

	N1	P1	N2	P2
Full-field	23 ±2	45 ±4	72 ±7	-
Hemi-field	37 ±4	53 ±4	81 ±6	-
p	*<0.01*	*>0.1*	*>0.5*	

AMPLITUDE (μV)

	N1	P1	N2	P2
Full-field	1.38 ±0.24	1.93 ±0.45	3.43 ±0.71	-
Hemi-field	4.75 ±0.75	5.40 ±0.67	7.49 ±1.13	-
p	*<0.001*	*<0.001*	*<0.01*	

Significance values refer to differences between the two modes of stimulation.

3. FLASH VER

The flash-evoked response typically consisted of two prominent negative components which were designated N1 and N2, separated by a positive deflection (P1) and followed (though not in all cases) by another positive deflection, P2 (Fig. 50). The effect of different stimulus intensities was investigated in a group of young subjects. As stimulus intensity decreased there was a prolongation of component latency (Fig. 51). N1 latency was significantly inversely correlated with flash intensity ($r= -0.47$; $p<0.01$). At 4.1 log units above threshold, the mean latency was 132 ±9 msec, while at 6.1 log units above threshold it was 107 ±6 msec. N2 latency also showed a significant inverse correlation with stimulus intensity ($r= -0.55$; $p<0.001$). Mean latency was 211 ±9 msec at 4.1 log units above threshold and 196 ±4 msec at 6.1 log units above threshold. Both P1 and P2 latency showed no significant correlation with stimulus intensity ($r= -0.18$; $p>0.2$).

The rise time of each VER component was not significantly correlated with stimulus intensity ($P>0.2$ in all cases) (Fig. 52).

There was a tendency for amplitudes to be smaller at the lower intensity levels. However, only for the N2 amplitude was a significant correlation present ($r= 0.30$; $p<0.05$). At 4.1 log units above photopic threshold, the mean N2 amplitude was 3.8 ±0.9 μV, while at 6.1 log units above threshold the mean amplitude was 6.4 ±0.9 μV. The amplitudes of N1, P1 and N2 did not vary significantly with flash intensity ($p>0.1$) (Fig. 53).

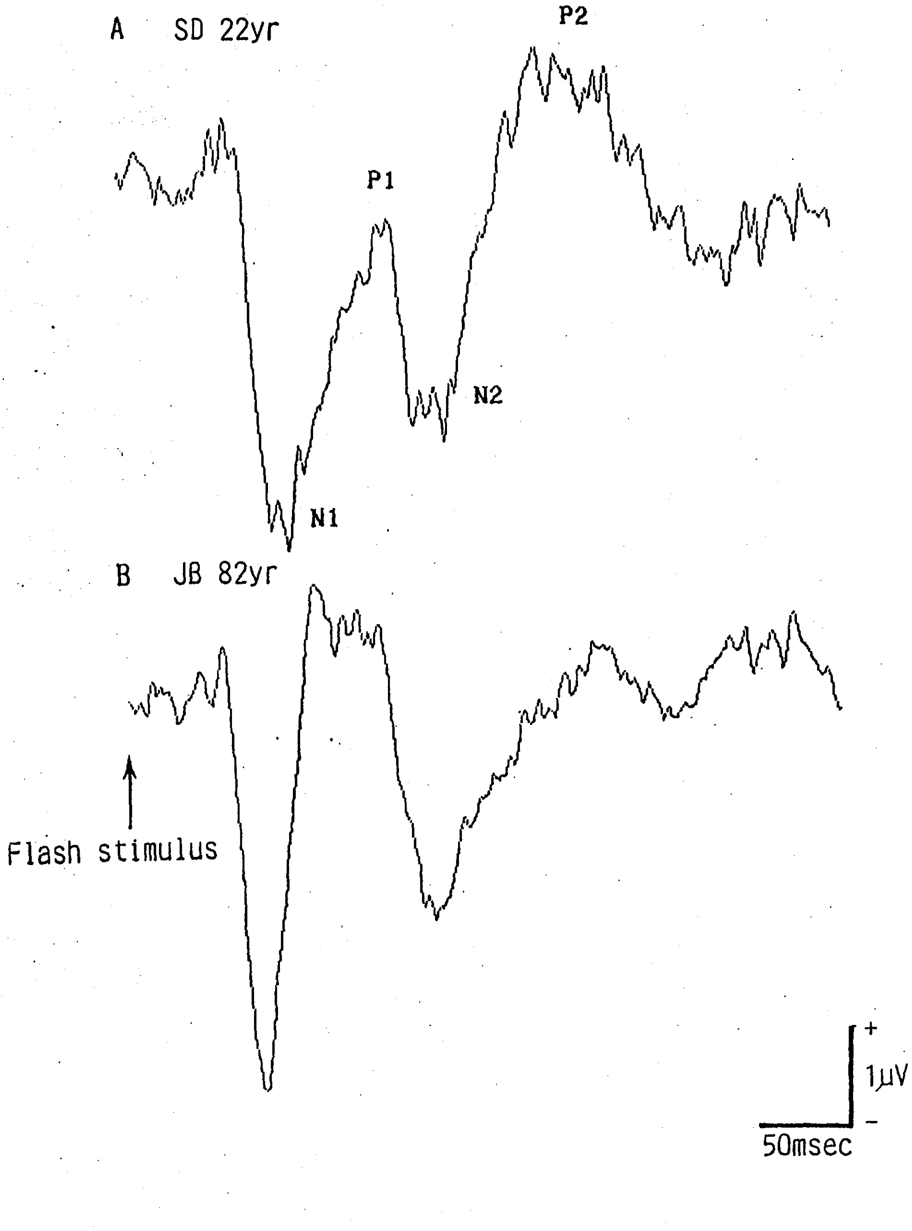


FIGURE 50. Typical VER to a flash stimulus of intensity 1.0 x 10^7 cd/m^2. (A) Young subject; (B) Old subject.

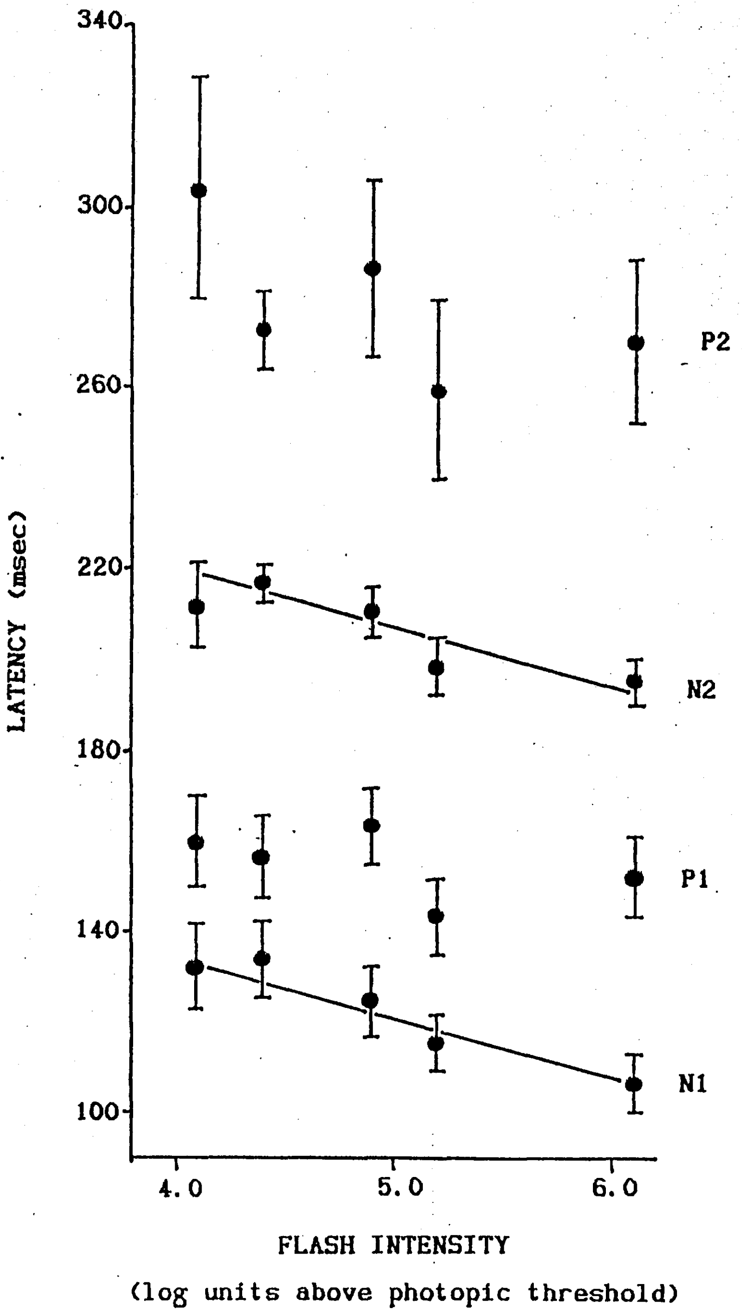


FIGURE 51. Effect of varying flash intensity on mean latency (± S.E.) of the four VER components.

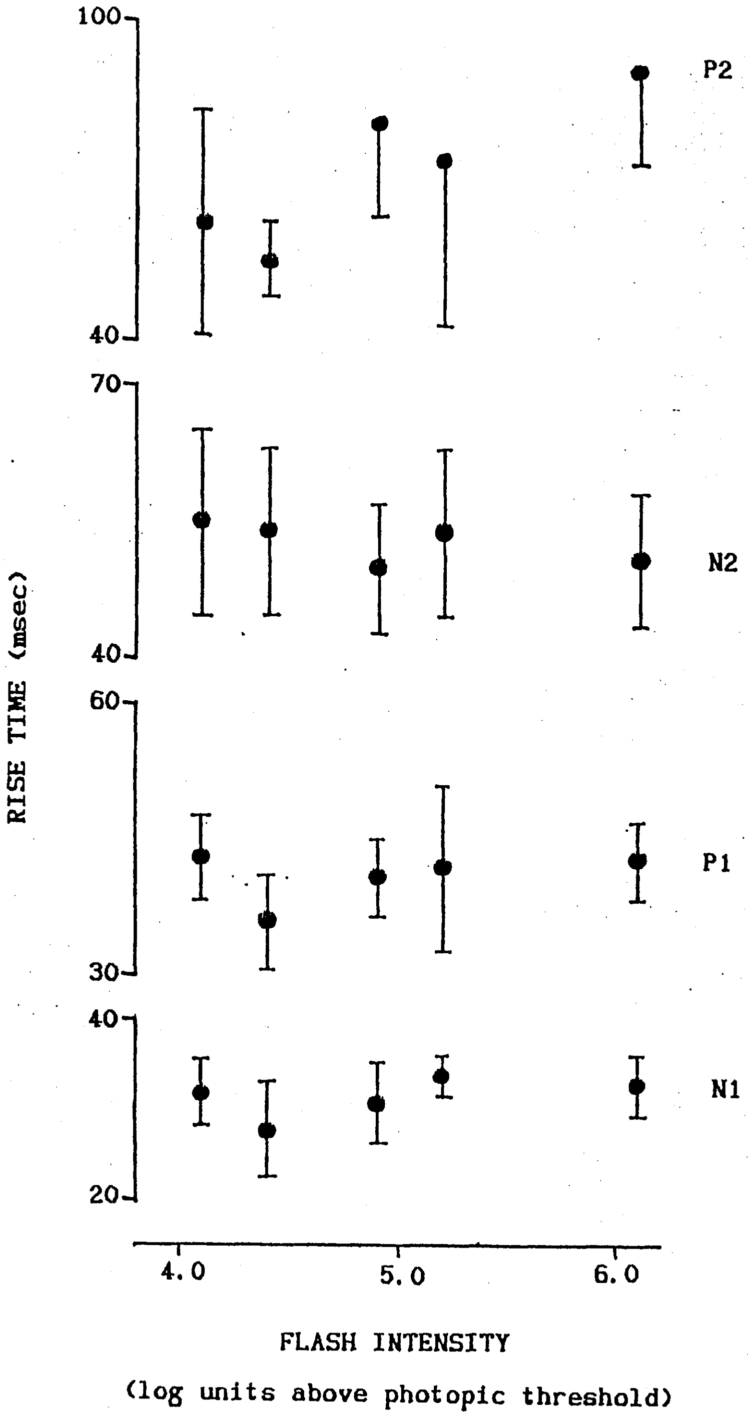


FIGURE 52. Effect of varying flash intensity on mean rise time (± S.E.) of the four VER components.

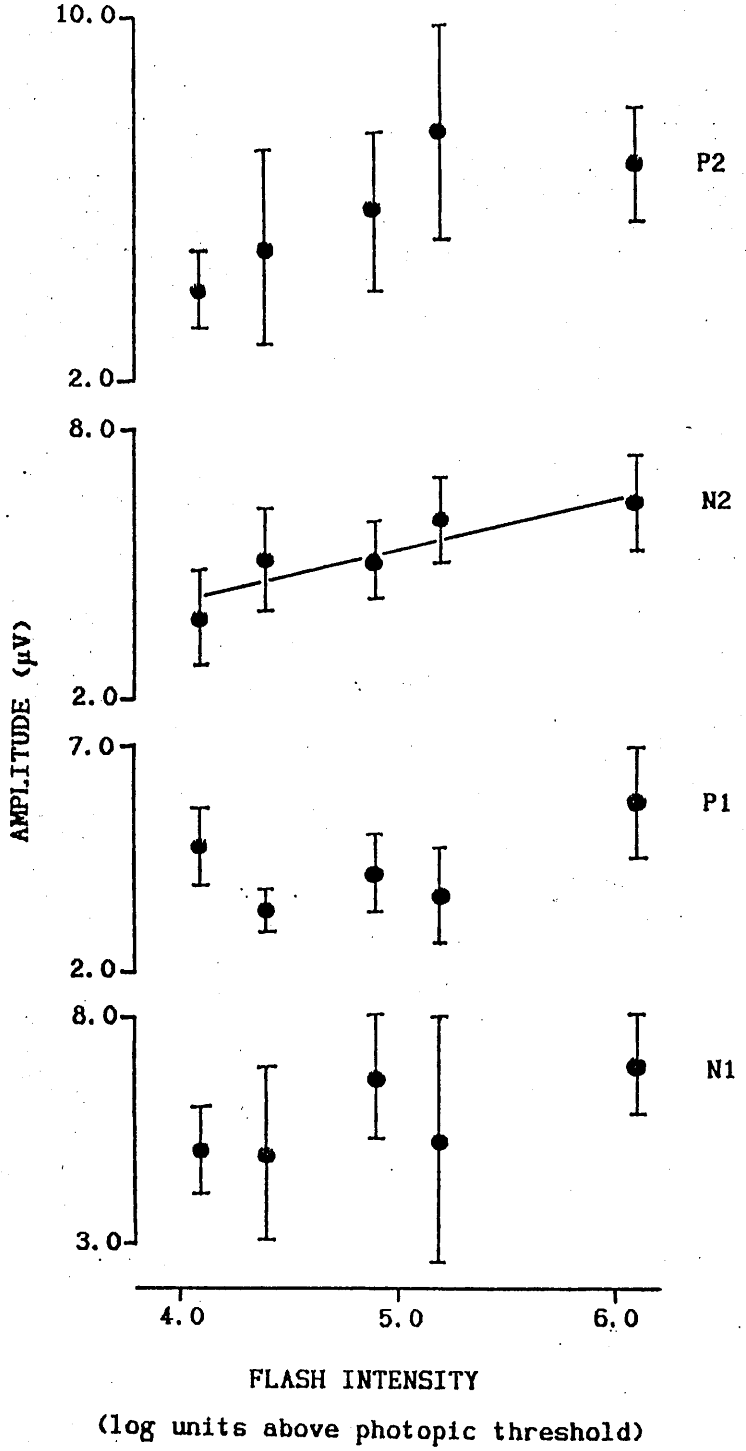


FIGURE 53. Effect of varying flash intensity on mean amplitude (± S.E.) of the four VER components.

Age-related changes

The VER in response to a 1.0 x 10^7 cd/m^2 was compared in young and old subjects (mean ages 22 yrs and 68 yrs respectively).

The mean latency of N1 was shorter in the young group compared with that of the old group although the difference was only of marginal significance ($0.05<p<0.1$). For P1, N2 and P2 the differences were not significant ($p>0.2$) (Fig. 54 and Table 29).

Although latencies were not significantly different in the two age groups, by inspection of the data it was apparent that the two earlier components, N1 and P1, had a shorter mean latency in the old subjects than they did in the young subjects. On the other hand, the two later components, N2 and P2, had longer mean latencies in the old group compared with those of the young group. A statistical comparison was made between young and old subjects in terms of the interval between N1 and N2 and between P1 and P2. It was found that the interval between the negative peaks was significantly longer in the old group than it was in the young group ($p<0.01$). The mean interval between the two positive peaks was also numerically longer in the old group although the difference was not significant ($p>0.2$) (Fig. 55 and Table 29).

There was no significant difference in the amplitude of N1, P1, N2 and P2 between young and old groups ($p>0.3$ in all instances) (Fig. 56 and Table 29).

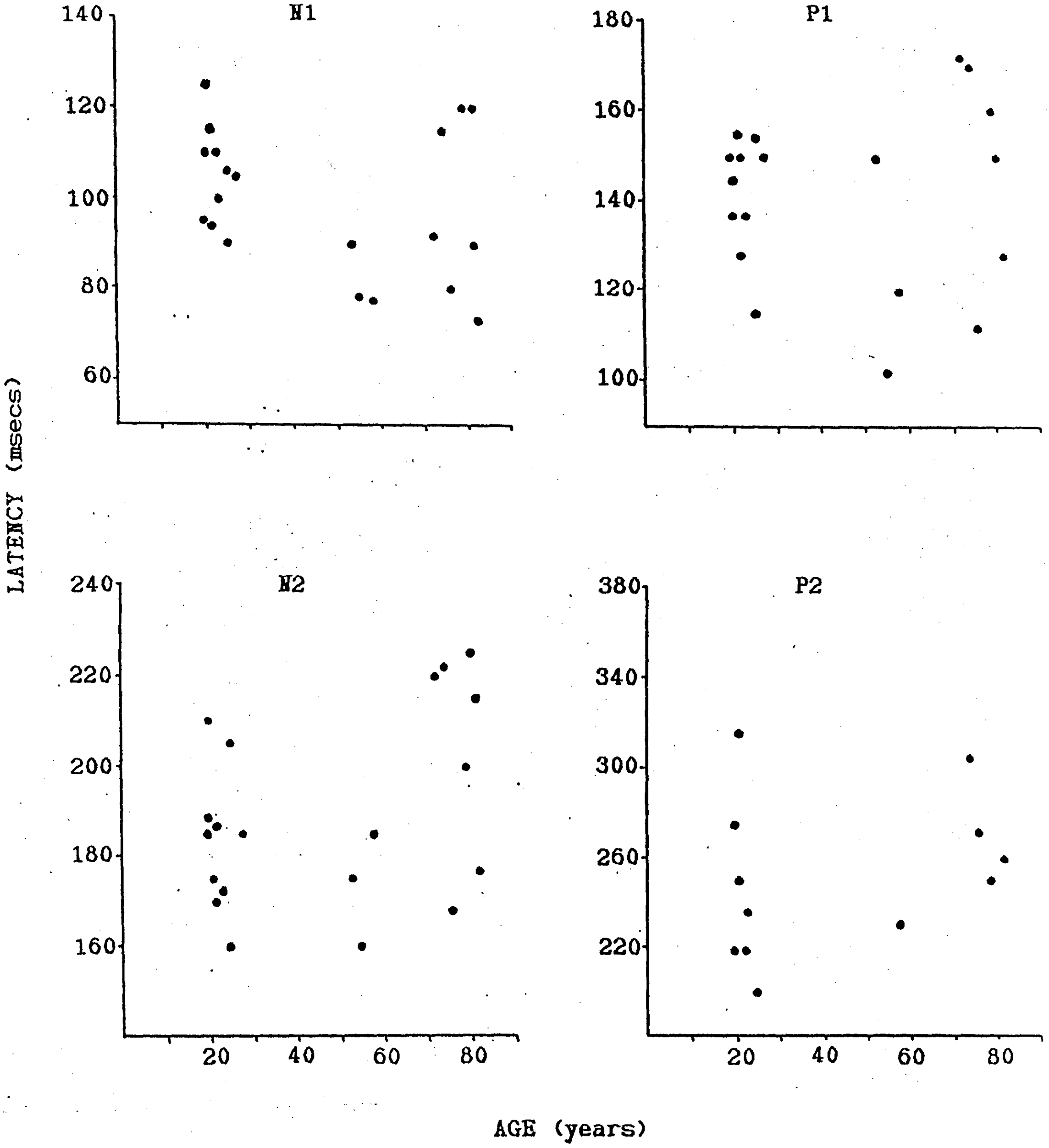


FIGURE 54. Effect of age on the latencies of the four components of the flash VER (intensity 1.0 x 10^7cd/m^2).

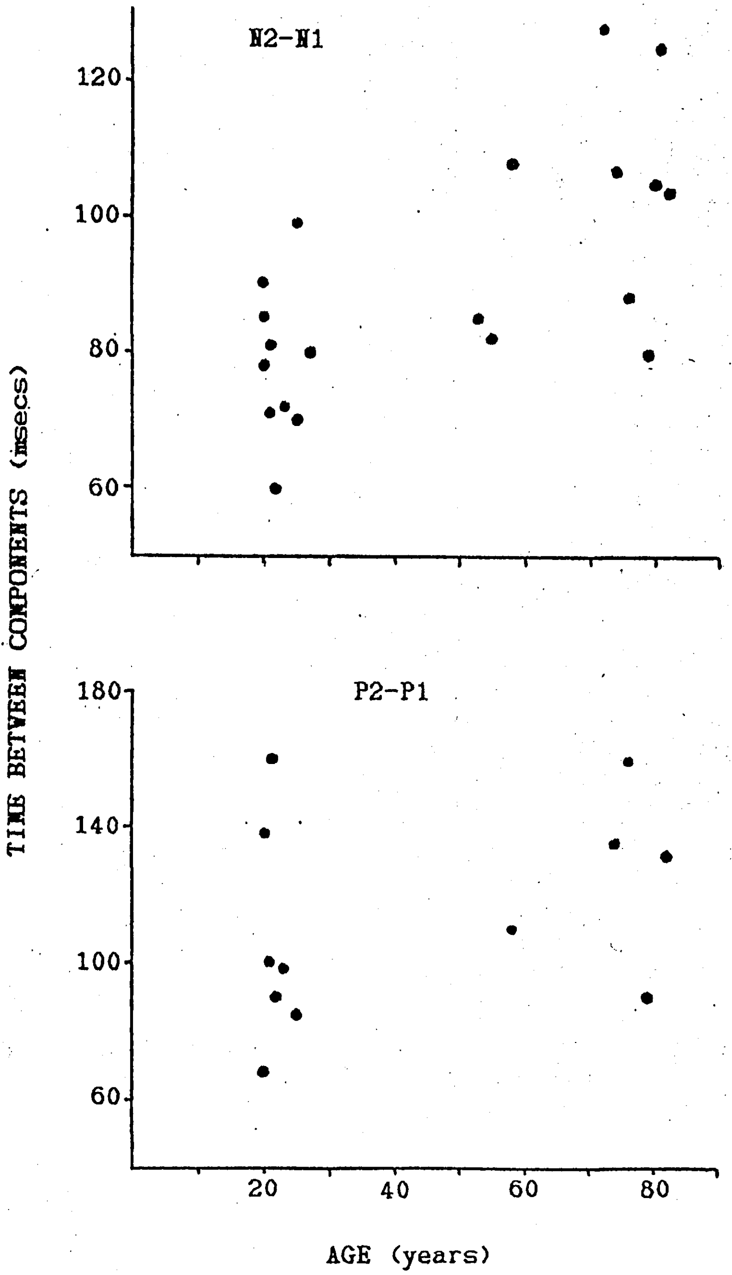


FIGURE 55. Effect of age on the time interval between the N1 and N2 components and between the P1 and P2 components of the flash VER (intensity 1.0 x 10^7cd/m^2).

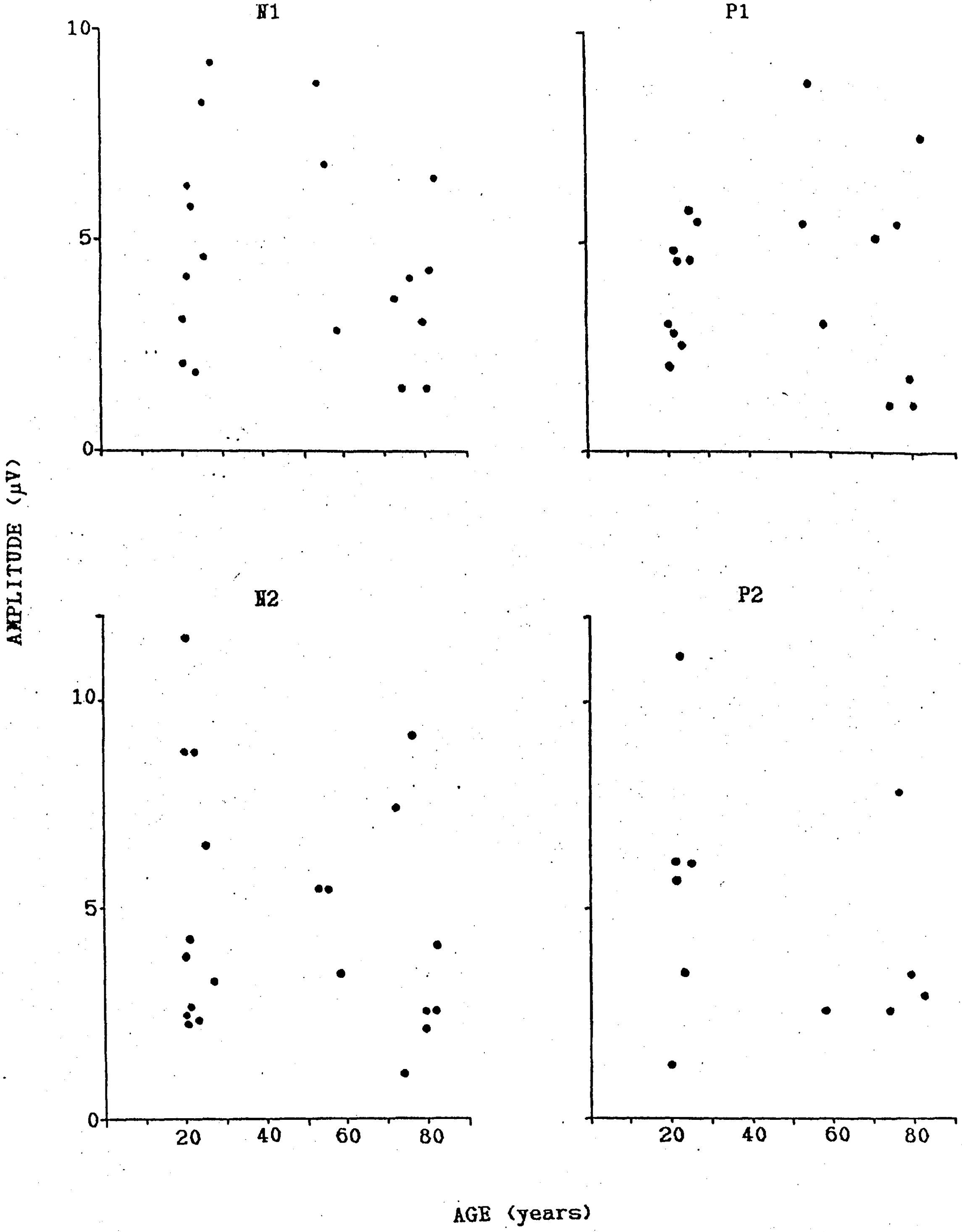


FIGURE 56. Effect of age on the amplitudes of the four components of the flash VER (intensity $1.0 \times 10^7 cd/m^2$).

Rise times were also compared (Fig. 57 and Table 29). Only in the case of N2 was there a significant difference between the age groups, rise time being longer in old subjects ($p<0.05$). For N1, P1 and P2 there were no significant differences between the two groups ($p>0.1$).

In general, then, the flash VER amplitudes and rise times showed little or no change with age. Latency also showed no significant age-related effects although the interval between the negative peaks was significantly longer in old subjects.

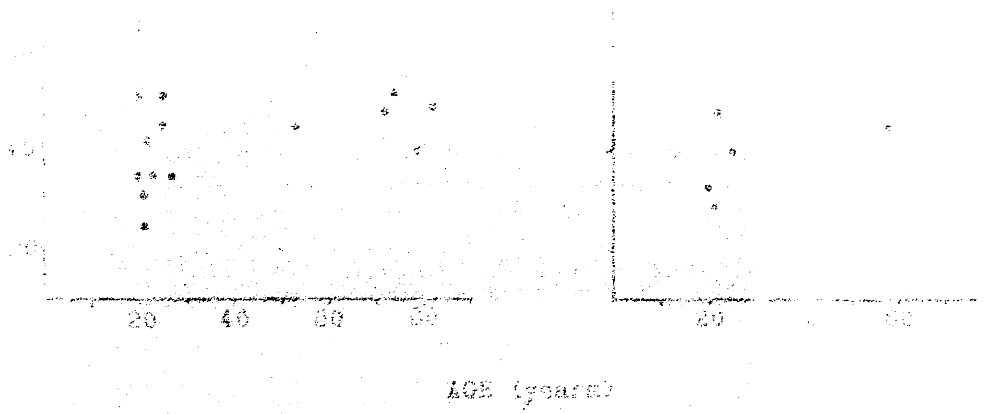


FIGURE 57: Effect of age on the rise times of the four components of the flash VER (intensity 1.0 [illegible]

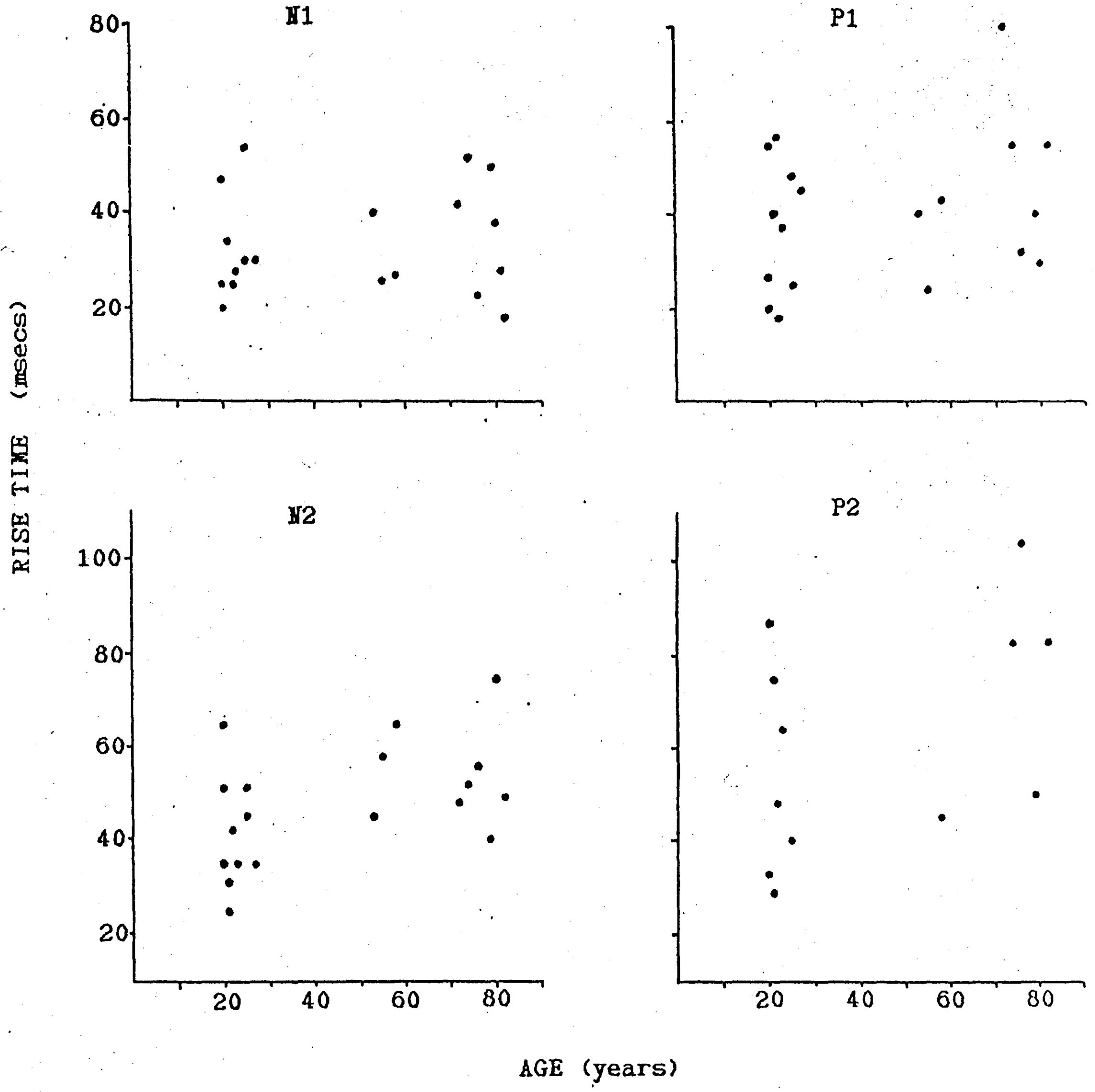


FIGURE 57. Effect of age on the rise times of the four components of the flash VER (intensity 1.0 x 10^7cd/m^2).

TABLE 29. Summary table showing mean values (± standard error) of characteristics of VER produced by a 1.0 x 10^7 cd/m^2 flash in young and old subjects.

AMPLITUDE (μV)

	N1	P1	N2	P2
YOUNG	5.0 ±0.9	3.9 ±0.5	4.8 ±0.9	5.6 ±1.3
OLD	4.3 ±0.8	4.4 ±0.9	4.4 ±0.3	3.9 ±0.9
p	*>0.5*	*>0.7*	*>0.7*	*>0.3*

LATENCY (msec)

	N1	P1	N2	P2
YOUNG	105 ±3	142 ±4	183 ±5	245 ±15
OLD	94 ±6	138 ±9	195 ±8	263 ±12
p	*0.05<p<0.1*	*>0.6*	*>0.2*	*>0.6*

RISE TIME (msec)

	N1	P1	N2	P2
YOUNG	32 ±3	37 ±4	42 ±4	54 ±8
OLD	34 ±4	39 ±6	54 ±3	73 ±11
p	*>0.6*	*>0.3*	***<0.05***	*>0.1*

INTERVAL BETWEEN PEAKS (msec)

	N1-N2	P1-P2
YOUNG	79 ±4	106 ±12
OLD	101 ±5	125 ±12
p	***<0.01***	*>0.2*

Significance values refer to differences between age groups.

DISCUSSION

FLASH VISUALLY EVOKED RESPONSE

Effects of different flash intensities

The response evoked by a brief flash stimulus contained four major peaks labelled according to their polarity and order of appearance after stimulation - N1, P1, N2 and P2. Their respective latencies were of the order 100, 150, 200 and 275 msec. Several previous studies have identified complexes of similar shape (e.g. Armington, 1964; Wicke, Donchin and Lindsley, 1964) though other studies have described VERs containing a greater number of waves (e.g. Cigánek, 1961; Rietveld and Tordoir, 1965; Straumanis et al, 1965) and with component latencies as short as 25 msec (Cobb and Dawson, 1960).

In the present work, inspection of the mean amplitudes across the range of intensities suggested that all of the components became larger as the flash intensity increased. Variation between subjects was wide, however, and only in the case of the second negative component was the correlation between amplitude and intensity found to be significant. Previous studies have served to indicate that the relationship of VER amplitude to intensity is by no means a simple one. Rietveld (1963) noted that certain components decreased in amplitude while others increased, a finding which was confirmed by Wicke et al (1964). Dustman, Shearer and Snyder (1982) described two groups of subjects - "augmenters" and "reducers" - designated thus according to the manner in which VER amplitude was related to intensity. Furthermore, Armington (1964) and Shipley, Jones and Fry (1966) pointed out that the amplitude / intensity relationship need not always be a monotonic one and that, for some components, a reduction in amplitude was sometimes seen at highest intensities, in a way which is displayed by component P2 in the mean data of the present study - see Fig. 53 - and which was sometimes observed in individual subjects.

Examination of the present data also suggested that each of the four peaks showed a tendency towards shorter latencies at higher flash intensities. However, only the two negative waves, N1 and N2, showed a significant correlation between latency and luminance. P1 and P2 both appeared to have a wider scatter between individuals than did the negative peaks. The finding that the latency of at least some of the components was significantly correlated with flash intensity is one which is in general agreement with previous studies. Shipley et al (1966) noted a tendency for all latencies to decrease as luminance was increased, the reduction being of the order 25-35 msec per log unit. More in keeping with the present work (where the reduction in latency was of the order 5 msec per log unit) are the findings of Wicke et al (1964) who observed that luminance-related latency changes only occurred in the two major negative peaks which they had identified, decreasing by approximately 40 msec over 5 log units. Rietveld and Tordoir (1965), although identifying a much larger number of waves, similarly found that only in the two larger negative complexes (which they designated B and E) was there a correlation of decreasing latency with increasing luminance.

In the present study, rise times showed no significant correlation with intensity. The data showed wide variation between subjects and visual inspection of the mean data revealed no obvious trends.

Effects of ageing on the flash VER

While the flash stimulus was used primarily to check the responsiveness of the subject and the integrity of the recording set-up prior to stimulation with the grating pattern, sufficient data were obtained to permit an analysis of the effects of ageing.

The latencies of the respective components were not significantly different between young and old subjects (see Table 29), though the interval between N1 and N2 was significantly longer in old than in young subjects (Table 29). The corresponding comparison of the P1-P2 interval showed no significant age-related effect (although the mean interval was numerically greater in old subjects).

These results are not consistent with previous studies, which have all noted an increased latency in older subjects (e.g. Straumanis et al, 1965; Buchsbaum et al, 1974; see Table 5). Why, then, should the present work find no significant age-associated latency changes and why should there be the apparent dissociation in the behaviour of early and late VER components? The reason may lie in the use of a higher flash intensity than has previously been employed. Many of the above studies used stimuli which were of a much lower luminance than that used in the present study (e.g. 7.0 cd/m^2 in Dustman and Beck, 1966; 68 cd/m^2 in Wright et al, 1985). The apparent discrepancy in the present work might be related to the comparatively high intensity which was used (10^7 cd/m^2). It has been postulated that a reduction in evoked response amplitude at high intensities might be due to an inhibitory mechanism which protects the cortex from over-stimulation (Silverman, Buchsbaum and Henkin, 1969; Lukas and Siegel, 1977). Dustman and Snyder (1981) suggested that larger VERs in old subjects were a result of reduced efficacy of this cortical inhibitory function. If such a high-threshold inhibitory mechanism also manifests itself in temporal terms then this might account for the absence of age-related latency changes in the present study. The fact that the N1-N2 interval was significantly increased in old subjects suggests that the age-related loss of inhibition manifests itself more strongly at N1 (where the mean latency was numerically shorter in old subjects compared with young) than it does at N2 (where the mean latency was numerically *longer* in old subjects). This would be consistent with those studies which found an age-related increase in amplitude only in short-latency components (Dustman and Beck, 1969; Man'kovskii et al, 1978).

In the present study, no significant differences were present between the amplitudes of corresponding components in young and old subjects. A similar lack of amplitude change has been reported by Wright et al (1985) and LaMarche et al (1986). Other studies have produced conflicting reports, much of the dissension probably attributable to methodological differences.

Inspection of the raw data suggested that rise times were slightly higher in old subjects for the two positive components and the second negative component. However, differences between rise times of corresponding components in the two age groups did not attain significance.

PATTERN VISUALLY EVOKED RESPONSE

Effects of ageing on the PVER to different contrasts

Latency

The relationship between latency and contrast was similar in young and old subjects: the latency of the N1, P1 and N2 components of the PVER was significantly inversely related to physical contrast, becoming more prolonged as log contrast was reduced. These findings correspond to those of previous studies on the effects of grating pattern contrast on the transient PVER. When contrast was reduced, Reed et al (1984) observed an increase in latency for both P1 and P2. Jones and Keck (1978), on the other hand, found only N1 to show a similar significant relationship. Parker et al (1982b) noted that the significant inverse relationship of latency to log contrast was confined to P1 (although they reported similar trends with all other peaks).* Using a psychophysical contrast matching technique, Cannon (1979) showed that there was a linear relationship of estimated subjective sensation (perceived contrast) with logarithm physical contrast. Hence, the relationship of objective with subjective contrast is one which appears to be of the same form as that of objective contrast with PVER latency.

* Kulikowski (1977) showed that P2 latency fell curvilinearly as log contrast was increased.

In the present study, the mean latencies of the four components of the PVER were, at virtually all contrasts, numerically greater in old subjects. Significant differences were present at each contrast level for N1 but appeared less frequently at each subsequent peak such that, for P2, in no instance did the difference between young and old groups reach significance (see Tables 6 and 8). As was noted in the VER Introduction, virtually all previous work in this area has concerned itself with the response evoked by reversal of a checkerboard pattern (see Table 5). Given the proviso that a straightforward comparison of the checkerboard reversal PVER and the grating pattern onset PVER may not be possible, the component latencies of each type of response appear to be similarly affected by age. Using checkerboard onset, Kriss et al (1984) reported greater age-related increases in latency than those observed with checkerboard reversal, the latter being similar in effect to pattern offset. Wright et al (1985) also noted age-related latency increases with checkerboard onset.

In the present work, statistical comparisons of the intercepts of the corresponding latency vs log contrast regression equations in young and old subjects showed that, for N1, P1 and N2, the intercepts were significantly higher in the old group. When the same regression equations were compared in terms of slope, no significant differences between young and old subjects were found. In other words, for each component the latency vs log contrast regression line for the old group was shifted upwards and parallel to that of the young group. Hence, an increment in log contrast produced the same decrement in latency in both young and old.

Since the grating patterns were presented at fixed physical contrasts, the increase in latency in old subjects could be attributable to the reduced psychophysical strength of the stimulus. In order to investigate this possibility a further series of experiments was carried out in which the stimuli were made psychophysically equivalent (i.e. 'normalized') by presenting the patterns at contrasts which were multiples of the pre-determined contrast threshold. In young subjects, a significant inverse relationship of latency to log normalized contrast was present at both spatial frequencies for all four components of the PVER. In old subjects, similar significant correlations were present for N1, P1 and N2 at 3 c/deg (with the relationship of P2 latency to log normalized contrast being of marginal significance). At 8 c/deg in old subjects a significant inverse correlation was present between P1 and N2 latency and log normalized contrast (after the omission of a single outlying point in each case). N1 latency was not significantly correlated with log normalized contrast - probably due to the small number of data points over a limited range of suprathreshold contrast - while P2 latency showed a correlation of marginal significance.

At 8 c/deg, making the stimuli psychophysically equivalent appeared to be effective in eliminating the N1, P1 and N2 latency differences between young and old subjects. The P2 component had a *shorter* latency in the old subjects which is consistent with the earlier finding that no significant differences in P2 latency were present between young and old subjects when 8 c/deg grating patterns of identical *physical* contrast were used. At 3 c/deg, however, the age-related prolongation in latency persisted even when grating pattern contrasts were made psychophysically equivalent. Hence, normalizing the stimuli was sufficient to eliminate the age-related differences at 8 c/deg but not at 3 c/deg.

How can this difference between the two spatial frequencies best be explained? The reason for what at first glance appears to be a disquieting anomaly may be related to the transient / sustained distinction outlined in the General Introduction and which was integral to the interpretation of certain aspects of the results of the Signal Detection experiments in the previous section. As was the case with the detection paradigm, there may be a slight problem in directly relating the contrast sensitivity findings to the PVER study. In both sets of experiments (SDT and VER), thresholds determined using an ascending method which involved a slowly changing stimulus were then used as reference points in paradigms which involved abruptly-presented stimuli (i.e. signal detection and the recording of the transient evoked response). Breitmeyer and Julesz (1975) compared contrast sensitivity obtained when the stimulus had an abrupt onset with that obtained when the stimulus had a gradual onset. It was found that, at spatial frequencies below *ca* 5 c/deg, contrast sensitivity was appreciably enhanced when abrupt presentation was used. In the present study, this enhancement was present in young people as shown by the fact that the intercept of the latency vs log contrast regression equations of both N1 and P1 was significantly greater at 8 c/deg than at 3 c/deg. That this difference was not merely a function of the lower apparent contrast of the 8 c/deg grating pattern was indicated by the significant differences in intercept which were present for young subjects even when the contrasts were made psychophysically equivalent (normalized): the regression equations of latency vs log normalized contrast for P1, N2 and P2 had significantly lower intercepts at 3 c/deg compared with 8 c/deg, while for N1 the difference was of marginal significance. In old subjects, on the other hand, there were no significant differences in the intercepts of the corresponding latency vs log contrast regression equations at 3 and 8 c/deg. This was also the case with the regression equations of latency vs log normalized contrast and hence suggests that the enhancement in contrast sensitivity with abrupt stimulus presentation at 3 c/deg in young people is lost in old people. Supporting this conclusion are the findings of Kline et al (1983) who, in both old and young subjects, compared contrast sensitivities with reaction times to grating pattern stimuli of different spatial frequencies. A significant inverse correlation was present between contrast sensitivity and reaction time in the young group; in the old group, the correlation did not reach the same level of significance, particularly at the three lowest spatial frequencies (0.5, 2.0 and 4.0 c/deg) where there was virtually <u>no</u> relationship between the two variables. This suggests that, for old subjects, contrast sensitivity at low spatial frequencies is not necessarily a good predictor of performance on a task involving abruptly-presented stimuli of low spatial frequency. In the present study, although young and old subjects were presented with psychophysically comparable stimuli, the psychophysical equivalence at 3 c/deg may only have prevailed when stationary patterns were used - when an abrupt onset was used the old subjects may have been additionally impaired in their perception of the pattern, this manifesting itself as an increased PVER latency. Hence, the present study provides objective electrophysiological evidence for the age-related impairment in the processing of transient stimuli previously shown by psychophysical techniques. The suggestion of a slightly steeper slope (though not significantly so) in the latency vs log contrast functions of N1 and P1 at 3 c/deg in old subjects (compared with young subjects) might be related to this 'additional' low spatial frequency impairment. This would be in keeping with the suggestion of Parker and Salzen (1977b) who tentatively proposed that the N1-P1 complex reflected the activity of the transient system (on account of the short latency and the large amplitudes at low spatial frequencies) and that the N2-P2 complex was a reflection of activity in the sustained system (since it had a longer latency and an amplitude which was attenuated at low spatial frequencies).

Amplitude

In the present data, in only one instance - the P2 component at 3 c/deg in young subjects - was there a significant relationship between log contrast and amplitude: as log contrast was increased so was the amplitude (see Table 12). This may be of consequence in the light of the findings of Kulikowski and Leisman (1973) who showed that P2 amplitude correlated with threshold for pattern detection when the stimulus duration was long, but that a similar correlation occurred for earlier components only when the stimulus duration was short. Inspection of the present data suggested that a similar trend was common to all other components in young subjects. Previous studies of the transient VER to grating pattern stimuli have indeed found that amplitude tends to be directly related to contrast (Jones and Keck, 1978; Parker et al, 1982b; Reed et al, 1984). In old subjects the trend was apparent at 8 c/deg. However, at 3 c/deg the amplitude of each component tended to be highest at the *lowest* contrast (3%), although between 40% and 5% there *was* a trend towards smaller amplitudes (although not at P2) (Tables 12 and 13).

No consistent significant differences were found between component amplitudes of young and old subjects although visual inspection of the data suggested that there was a tendency for amplitudes to be numerically higher in young subjects. Previous studies (using checkerboard reversal) have generally reported no significant age-related amplitude changes (e.g. Celesia and Daly, 1977; Halliday et al, 1982; see Table 5).

The comparison between young and old subjects was confounded by the differences in amplitude which were found to be present between male and female subjects within each age group. PVERs elicited by grating patterns of the same physical contrast tended to contain components of a larger amplitude in young males than in young females. Conversely, old females tended to have larger amplitude PVERs than did old males. Previous reports of sex-related differences in amplitude have generally found that females have a larger amplitude PVER than do males throughout the lifetime (e.g. Halliday et al, 1982; Allison et al, 1983; Mitchell et al, 1987). In the present study the amplitude of the male PVER tended to decrease with age at both spatial frequencies, while that of the female PVER tended to increase with age at 8 c/deg and remain relatively unchanged at 3 c/deg. It has been suggested that differences in skull thickness (Allison et al, 1983) or hormonal effects (LaMarche et al, 1986) may contribute to amplitude differences between males and females. If this is indeed so then it may be the case that age-related changes in the two parameters account for the apparent reversal of the amplitude differences with age which was observed in the present study. However, when stimulus contrasts were normalized, the sex-related differences within young subjects were no longer present which implies that the difference between males and females was a psychophysical one rather than one which arose from anatomical differences. Kline et al (1983) found that young women had a higher contrast sensitivity than did young men (which would not account for the higher amplitude PVER in *male* subjects) while there was no sex-related differences in contrast threshold in old age. Other studies have generally reported no differences in contrast sensitivity between male and female subjects (e.g. McGrath and Morrison, 1981; Ross et al, 1985).

No significant correlation was found between normalized contrast and amplitude. This was true for both age groups at both 3 and 8 c/deg. In one instance (N1 at 8 c/deg in young subjects) the relationship was marginally significant, amplitude showing a tendency to become larger at higher contrasts. The wide scatter of data made it difficult to determine by visual inspection whether there was any contrast-dependent trend in component amplitude.

Young and old subjects were also compared in terms of the amplitude of the PVER elicited by psychophysically comparable stimuli. At 3 c/deg, the amplitude of N2 at 20x and 10x threshold was significantly smaller in the old group. No significant differences between young and old subjects were found at 8 c/deg. This observation is consistent with the previous conclusion that, at 3 c/deg, old people are additionally 'handicapped' by an impairment in transient processing - an impairment which will, of course, only become manifest when abruptly presented stimuli are used.

Rise time

Rise time, which has not been measured in previous studies of age-related PVER changes, showed no significant correlation with log contrast for both age groups. For old subjects the same was true for log normalized contrast. However, for young subjects a significant inverse correlation *was* present between N1, P1 and N2 rise time and log normalized contrast. In the case of the old subjects, the lack of such a correlation may have been due to the fact that the range of contrast multiples encompassed a different range of physical contrasts from that which operated for the young subjects - saturation may have occurred in the PVER of the old subjects reducing the likelihood of a linear relationship reaching sigificance. The fact that no correlation was present for young subjects when log *physical* contrast was used is difficult to explain since the range of physical contrasts was comparable with the range of normalized contrasts. The most likely reason for the discrepancy would appear to be differences in sampling; a much greater number of subjects might be required in order to counteract the wide variation. No consistent age-related differences in rise time were observed.

Effects of ageing on the PVER to different spatial frequencies

Latency

The relationship of spatial frequency with component latency was similar in both young and old subjects. The latency of the two later components, N2 and P2, was characterized by a high degree of variation between subjects and showed no significant correlation with spatial frequency. The two early components, N1 and P1, became prolonged as the stimulus spatial frequency was increased from 1 c/deg to 15 c/deg. These results are in keeping with those of Parker and Salzen (1977a) who, increasing spatial frequency from 0.5 to 10 c/deg, noted similar significant latency increases in N1 and P1 but non-significant changes with N2 and P2. Parker, Salzen and Lishman (1982b) observed a rise in P1 latency when increasing the spatial frequency of the grating pattern from 0.5 to 8 c/deg. Other studies have also indicated that only the earlier component latencies are affected by spatial frequency: Jones and Keck (1978) observed consistent latency changes only with N1 while Plant, Zimmern and Durden (1983) found only N1 and P1 to be thus affected, P2 latency showing high variation between subjects and demonstrating no consistent change with spatial frequency. However, these latter two studies differ from the present and above cited work in that the relationship which they observed between spatial frequency and latency was not a monotonic one. In both these studies, the latency was at a minimum at or near the peak of the contrast sensitivity function: 4 c/deg in the case of Jones and Keck (1978), and 2 c/deg in the case of Plant et al (1983). Reed, Marx and May (1984) also observed that latency was curvilinearly related to spatial frequency, decreasing when frequency was increased from 0.5 to 2 c/deg and increasing when frequency was further increased from 2 to 8 c/deg. Indeed, the latter study observed a similar relationship for both P1 and P2.

Since the perceived contrast of the stimulus will be dependent on its spatial frequency then one might indeed expect that the relationship of latency to frequency would follow the shape of the contrast sensitivity function, assuming that latency is related to the psychophysical strength of the stimulus. However, Plant et al (1983) suggested that, at lower spatial frequencies, the presence of an additional early component produced latency measurements which might have accounted for the observed deviation from a monotonic relationship between spatial frequency and latency. Jones and Keck (1978) also observed an early component which was peculiar to low spatial frequencies (<3 c/deg) and which they labelled N_o-P_o. In the present study, no such early component was consistently observed. In fact, Plant et al (1983) noted that the early double peak was not found in some subjects while in others a large field size was necessary to elicit it. This study used a stimulus with a 10 deg visual field as did Jones and Keck (1978). An 8.5 deg circular field was used by Reed et al (1984). In the work of Parker and Salzen (1977a), Parker et al (1982b), and in the present study, field sizes were rather smaller than the above.

A possible explanation for the observed monotonic relationship between PVER latency and spatial frequency lies in the manner in which the stimuli were presented. In a typical threshold determination, the grating pattern stimulus is invariably presented gradually. Under these circumstances, the characteristic loss in sensitivity at high and low frequencies becomes apparent. In the recording of a VER, the stimulus is generally presented with an abrupt onset. Given that the transient system predominates at lower spatial frequencies (Tolhurst, 1973) it is perhaps not surprising that a stronger response (i.e. a shorter latency) should occur when abruptly-presented low spatial frequency stimulation is used and should, to some extent, counteract the fact that the stimulus is at an ostensibly lower contrast. A similar explanation would pertain in those reaction time studies which have found a monotonic relationship between simple reaction time and spatial frequency (Breitmeyer, 1975; Vassilev and Mitov, 1976).

However, from earlier results in the present study it was surmised that old subjects were impaired in the processing of transient stimuli. If this were the case then one might expect that, in the old group, the relationship between latency and spatial frequency would be curvilinear rather than monotonic, more closely mirroring the shape of the contrast sensitivity function. The fact that the form of the relationship was similar in both young and old subjects suggests that the age-related transient impairment is not manifest when a relatively high contrast (40%) stimulus is used.

At each spatial frequency, the mean PVER latencies of old subjects were found to be numerically greater than those of young subjects. The N1 component was always significantly longer in old subjects, the P1 component at all spatial frequencies bar 2 c/deg and 15 c/deg, the N2 component at 3, 5 and 8 c/deg, and the P2 component at none of the spatial frequencies tested.

It might be tempting here, to draw comparisons with those psychophysical studies of the age-related decline in contrast sensitivity where the ageing effect was most apparent at medium spatial frequencies (McGrath and Morrison, 1981; Kline et al, 1983). If the components of the PVER reflect different levels of information processing then it may be the case that the more 'levels' affected then the more profound will be the psychophysical expression of the impairment. Since, at medium spatial frequencies, the latencies of the first three components were significantly prolonged with age it might be expected that this would be reflected in the psychophysical processing of these patterns. The higher and lower spatial frequencies, where significant latency changes were only present for N1 and not for the later components, might be less affected psychophysically.

The problem with this interpretation - even if one ignores the fact that the level of significance is not an indication of the *magnitude* of the difference - is that in all subjects, irrespective of age, only the latencies of N1 and P1 showed a significant correlation with spatial frequency. Since the latencies of N2 and P2 seem unaffected by these features then it would perhaps seem unlikely that changes in these latencies with age are related to the processing of spatial frequency information.

Alternatively, the difference in the response characteristics of the early and late components might be indicative of a distinction which some workers draw between different components of the VER (see Regan, 1972). Those which appear in the period immediately or closely following stimulation are sometimes labelled 'exogenous'; those appearing later are sometimes designated 'endogenous'. This nomenclature is intended to distinguish those components which are influenced primarily by the physical characteristics of the stimulus (exogenous) from those which are held to be more dependent on higher-level psychological processes (endogenous).

In any case, the comparison of PVER latency between the two age groups across the range of spatial frequencies provides general confirmation of the results obtained with 3 and 8 c/deg grating patterns over a range of contrasts.

Amplitude

In the present study, the amplitude of P1 and N2 in young subjects was significantly inversely related to spatial frequency - as the spatial frequency increased, the amplitude diminished. N1 and P2 showed no significant relationship with spatial frequency. In the case of old subjects, none of the four PVER components showed a significant change in amplitude as spatial frequency was increased. Previous studies have shown amplitude to be related to spatial frequency although, as with latency, the relationship appeared to be one which was dependent on the shape of the contrast sensitivity function. Early components (N1 and P1) have been observed to have a peak amplitude at around 4 c/deg or higher (Jones and Keck, 1978; Plant et al, 1983; Reed at al, 1984) while later components N2 and P2 had a maximum amplitude at 1 - 2 c/deg (Plant et al, 1983; Reed et al, 1984).

There were no consistent differences between the amplitude of the N1 and P1 components of young and old PVERs across the range of spatial frequencies tested. On the other hand, the amplitude of N2 and P2 were in all instances numerically larger in young subjects. However, the difference was significant in only one instance (P2 at 10 c/deg). In general, then, the lack of significant differences in PVER amplitude between young and old groups across the range of spatial frequencies at 40% contrast confirmed the findings obtained with 3 and 8 c/deg grating patterns of different contrasts.

The question remains as to why the spatial frequency / amplitude relationship displayed by P1 and N2 in young subjects should not be present in old subjects. The lack of correlation in the older age group might be indicative of an increased variability with age. However, examination of the results shows that the data in the old group are no more scattered than in the young group. Other interpretations are possible. If the contrast sensitivity function of old subjects is characterized by a 'flattening' as well as a 'narrowing' (McGrath and Morrison, 1981; Kline et al, 1983), then the range of perceived contrasts bounded by the contrast threshold 'envelope' is going to become smaller. For example, to a young subject grating patterns of medium and high spatial frequency and identical physical contrast might have perceived contrasts which were very different. To an old person the difference in perceived contrast might be less apparent. If amplitude is, as some previous studies have suggested (Jones and Keck, 1978; Parker et al, 1982b), an indicator of stimulus intensity, then the responses evoked by the above stimuli would have amplitudes of greatly different value in young subjects but perhaps only of marginally different values in old subjects.

However, another possible explanation is that, in old subjects, the PVER at 15 c/deg was to some extent contaminated with entrained alpha rhythm, resulting in responses containing components of larger than normal amplitude, and hence reducing the significance of an inverse correlation between amplitude and spatial frequency. Since a stimulus of this spatial frequency would appear psychophysically less powerful to old subjects, the occurrence of the alpha wave would perhaps be more likely in these subjects than it would be in young subjects. In fact, this tended to be the case. If one examines the data from the old subjects (Fig. 39) then it is clear that at 15 c/deg the amplitudes of all four components are somewhat higher than those of the corresponding waves at lower spatial frequencies. Indeed, there appears to be a similar, though slighter, tendency in young subjects. When the values at 15 c/deg are omitted, linear regression of the P1 and N2 data for old subjects does show a greater (though still non-significant) correlation of amplitude with spatial frequency than when the high spatial frequency data are included.

Rise time

Rise time behaved in a similar fashion to amplitude: in both young and old subjects the rise times of P1 and N2 (but not N1 and P2) were significantly inversely correlated with spatial frequency, becoming shorter as spatial frequency was increased. The significance of these latter results depends to a large extent on whether one considers rise time to be more closely related to the latency or to the amplitude of the response. For instance, one might expect a strong stimulus to evoke a 'strong' response - one with a short latency and which reached its peak faster (i.e. had a short rise time). Indeed, there *was* a tendency for the longer latency components to have a longer rise time. However, a more meaningful relationship might be that of rise time and amplitude, with the former perhaps being a more robust indicator of the processes underlying the generation of the PVER (since amplitude can be affected by such factors as skull thickness and electrode contact). Since, in the present study, amplitude and rise time appeared to be similarly related to spatial frequency then it would seem that the second interpretation is more appropriate.

Significance of PVER changes to age-related visual deficit

The signal detection theory experiments showed that changes in decision-making could not account for the reduced contrast sensitivity with age. Instead, the decline may be surmised to arise at some earlier stage in the processing of visual information. How do the results from the VER experiments bear on the question of the possible location of the age-related changes underlying the functional deficits? The most consistent finding was the increased latency of the PVER in old subjects. This was most apparent for the earlier components of the evoked response, N1 and P1. Amplitudes showed a tendency to be somewhat smaller in old subjects although not to a significant extent. How could these changes arise and how do they relate to visual information processing?

It has been shown that the latency of the PVER can be influenced by the pupil diameter of the observer (Hawkes and Stow, 1981; Tobimatsu, Celesia and Cone, 1988). Furthermore, Cant, Hume and Shaw (1978) and Trick et al (1986) showed that reducing retinal illuminance using neutral density filters caused an increased PVER latency. Since one consequence of ageing is senile miosis, it is possible that the resultant reduction in retinal illumination is contributing to the increased latency of the grating pattern VER in old subjects. However, the contribution is likely to be minimal. In the above studies a reduction in pupillary diameter and in retinal illuminance (0.5 log units) similar in extent to those occurring with age (Weale, 1961) produced latency increases in the order of 5 msec. In the present study the latency changes were much greater and hence cannot wholly be accounted for in terms of pupillary constriction. Indeed, Kriss et al (1984) found no significant relationship between natural pupil size and either latency or amplitude of the PVER in subjects of different ages.

There is the possibility that retinal changes might play a contributory role. Pattern ERG latency changes with age have been observed in humans (e.g. Weleber, 1981; see General Introduction). However, it seems likely that the delay in the PVER with age is due to changes both at and subsequent to the retina. Celesia, Kaufman and Cone (1987) made simultaneous recordings of checkerboard reversal pattern electroretinograms and visually evoked responses in subjects of different ages. In addition to age-related latency increases in the major components of both the PERG and the PVER, the retino-cortical delay between PERG and PVER was found to be significantly increased with age, indicating that the longer latencies of the PVER components were not merely a consequence of the retinal changes.

It is possible that demyelination in the visual pathway might account for the increase in PVER latency with age. Such delays are often seen in the PVER of patients with multiple sclerosis (Asselman et al, 1973). There is indeed some evidence that the process of myelin regeneration becomes less effective with age (Wisniewski and Terry, 1976). A reduction in axon numbers in the optic nerve (Johnson, Miao and Sadun, 1987) might also contribute to the delay in the PVER. Other possible contributing factors are the reduction in the number of neurons in the cortex itself (Devaney and Johnson, 1980), axonal and dendritic degeneration (Scheibel and Scheibel, 1975), and neurotransmitter imbalance (Samorajski, 1981) (see General Introduction).

Early components of the PVER are generally held to arise from striate cortex while later components are considered to have their origin in extrastriate cortex, although other interpretations are possible (see VER Introduction). Since significant age-related increases in latency were observed for N1 and P1, it would appear that the structural changes underlying the perceptual deficits occur either in or prior to the primary striate cortex. The fact that making the stimuli psychophysically comparable in young and old subjects was effective in abolishing the major differences in the young and old VER (at least at 8 c/deg where the 'extra' transient impairment is not as relevant) also indicates that the locus of the change must be at or prior to the site of recording. Increases in N2 and P2 latency might be suggestive of extrastriate changes or might merely be a consequence of the earlier delays in the information processing sequence. The fact that the latency increases exhibited by the later components appear to be no more than would be expected as a result of the earlier delay (i.e. the interval between components remains relatively constant) suggests that the processing of information at this level is largely unchanged with respect to young. This is also indicated by the fact that generally there were no consistent differences in rise time between young and old subjects. Alternatively, N2 and P2 might not be consequent upon the earlier waves but might be indicative of some parallel aspect of processing or of some 'higher level' processing which is less concerned with stimulus characteristics - hence the lack of significant differences between age groups in the latency of these later components (particularly that of P2).

How the above delays in latency might be related to the age-related reduction in contrast sensitivity is a matter for conjecture. It is difficult to see how the brain could utilise latency as a means of representing an aspect of visual information such as pattern contrast since this would require the existence of some earlier fixed temporal reference point from which the later events could be measured. It may be the case that latency changes are not a strict reflection of changes in perceptual experience but are merely epiphenomenal with respect to underlying physiological processes which are more closely related to perception.

Visual information is transformed at the retina into electrical signals which are then passed onto higher levels. A naive interpretation of the process of seeing would be one which regarded these signals as being subsequently reconstructed into a visual representation of the world. In other words, the data are first of all encoded and then decoded. This model of perception is one which requires the existence of an 'inner eye' which views the reconstructed scene. Such an interpretation obviously begs the question as to how exactly the process of vision operates. When studying the visually evoked response there is a danger of regarding the VER in a similarly naive manner by imagining it as containing implicit information which is somehow deciphered at higher centres; the characteristics of the VER (whether latency or amplitude) are seen as embodying specific aspects of the visual scene, while the 'higher centres' perform operations or analyses similar to that of the psychophysiologist, i.e. 'measurement' and interpretation of the VER. It should be remembered that the average evoked response is a somewhat artificial and stylized version of the 'real-life' entity. Furthermore, the generation of a VER is dependent on the presentation (or reversal) of a pattern - in either case there is a change in the visual information. The process of seeing, however, is not dependent on such changes - a grating pattern still looks like a grating pattern even when constantly present and stationary and presumably not generating a visually evoked response (or at least not one of the sort familiar to experimenters - there is the possibility that involuntary eye movements, which are known to be necessary to avoid disappearance of the image (Ditchburn and Ginsborg, 1952), somehow 'renew' the inflow of information, although it hardly seems likely that this process would involve the generation of the typical VER).

One can conclude from the present results that the age-related deficit in visual performance (as evinced by the reduction in contrast sensitivity) is mirrored by changes in the physiological processing of the same stimuli - changes which take the form of significant latency increases and a tendency towards smaller amplitudes of the grating PVER, and which are most likely located at a relatively early stage of the processing sequence, at or prior to the striate cortex. It is not possible to specify the exact nature of the relationship between the psychophysical and psychophysiological data (i.e. whether correlative or causal, and, if the latter, in which direction the causality acts - in other words, does the pattern have a lower apparent contrast because the electrophysiological information is delayed, or is the electrophysiological information delayed because the pattern has a lower apparent contrast?). However, once the information reaches higher decision-making centres the manner in which the older person acts upon it appears to be not significantly different to that of the young person.

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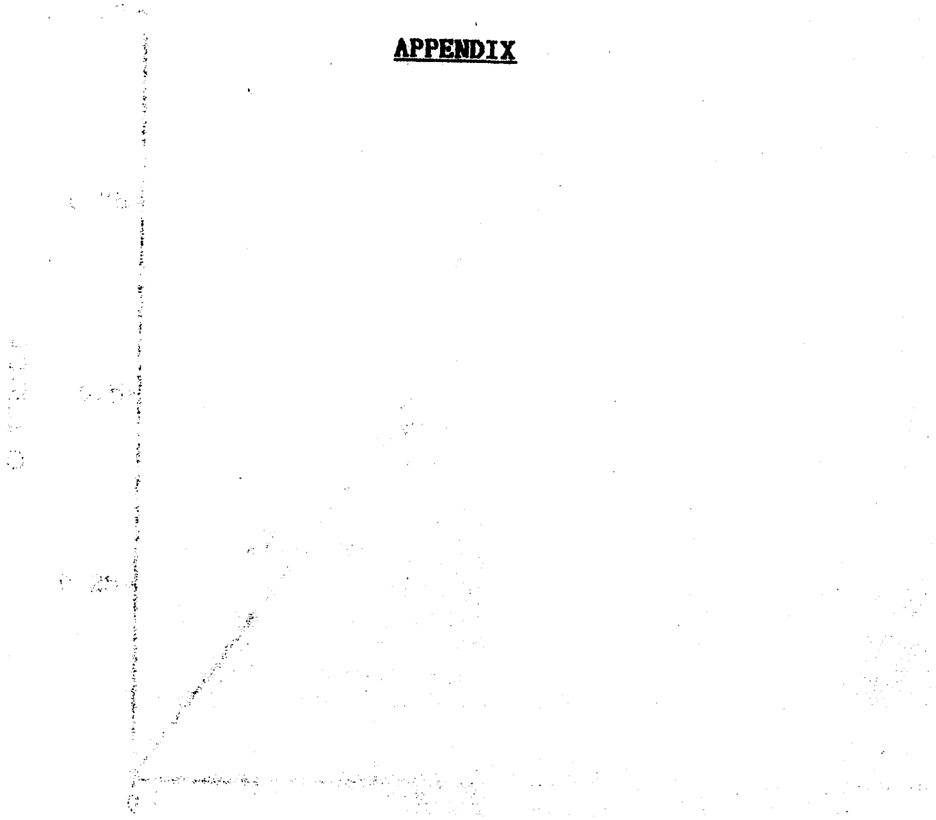
APPENDIX



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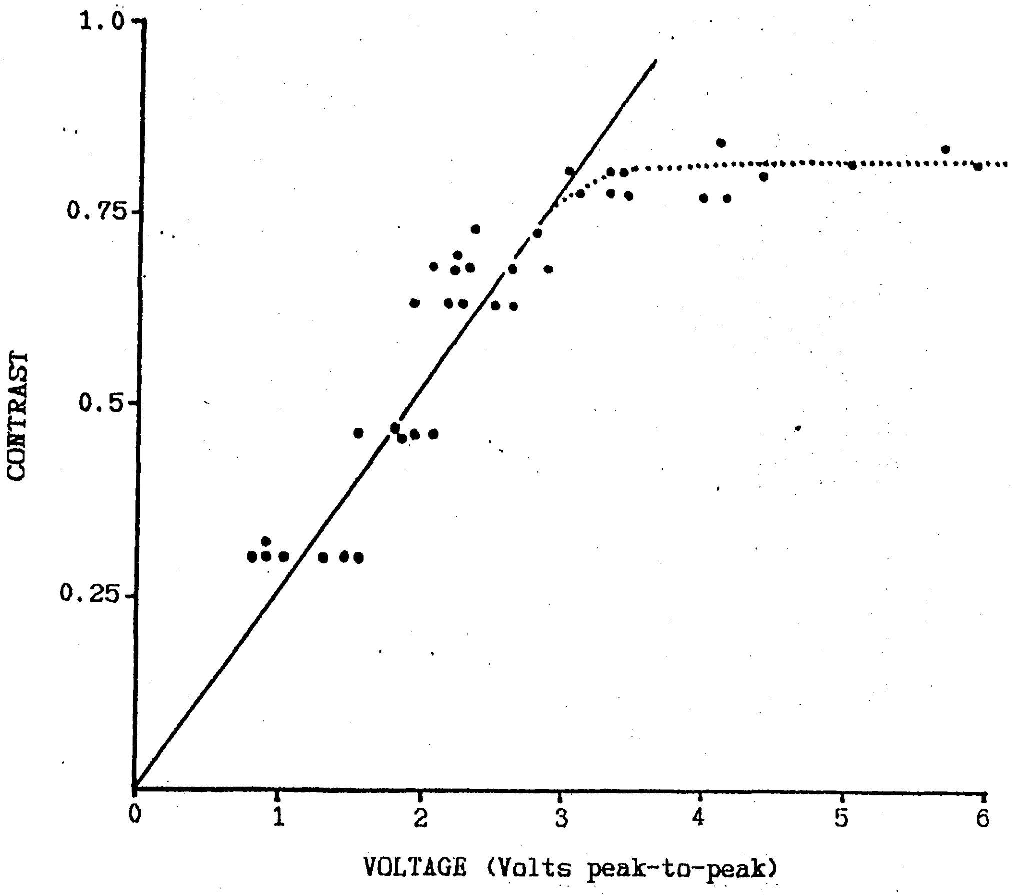

FIGURE 1. Relationship of grating pattern contrast to Z-modulation voltage for Tektronix 606B oscilloscope used in SDT experiments (see pg. 58).

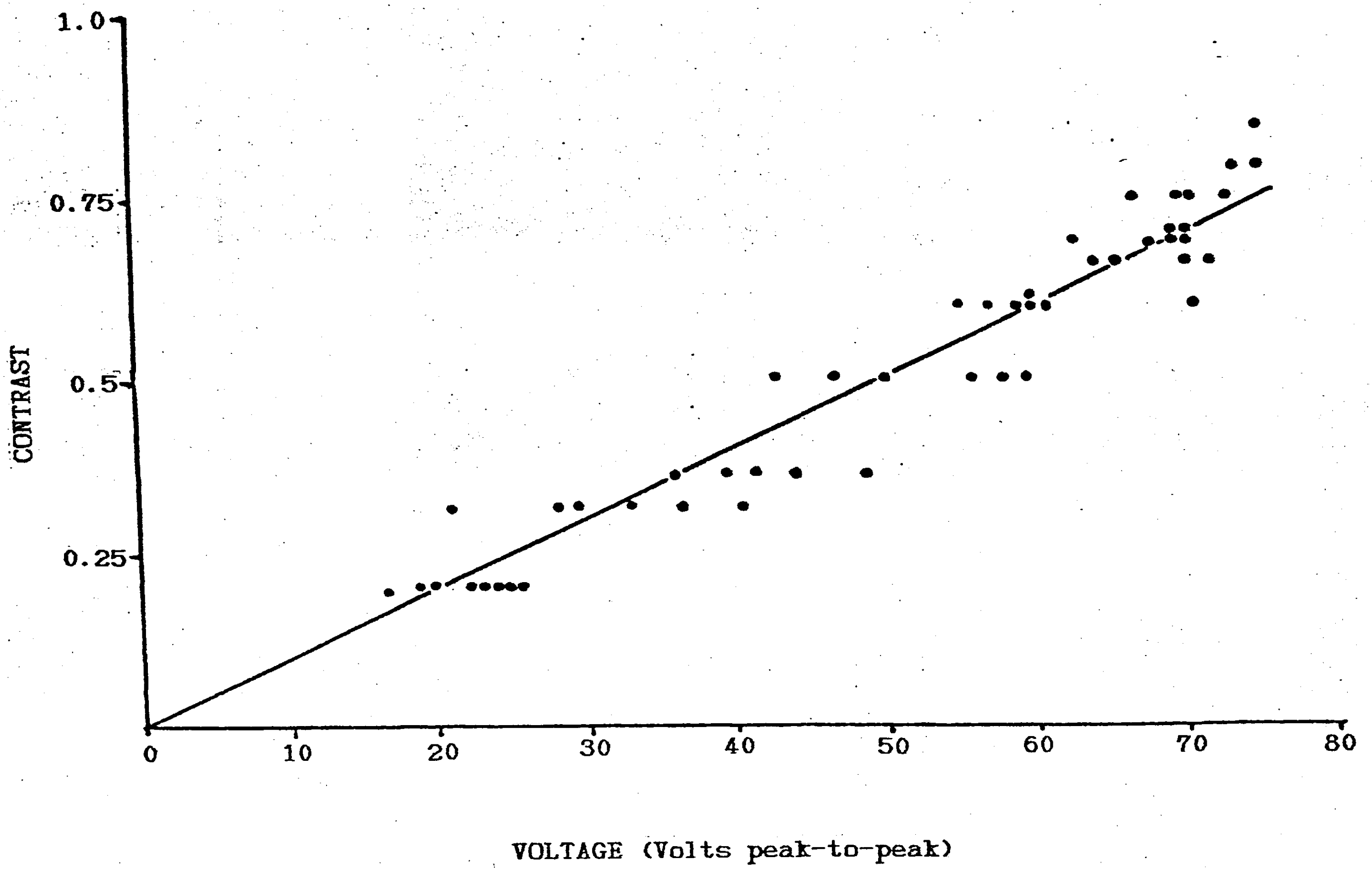

FIGURE 2. Relationship of grating pattern contrast to Z-modulation voltage for Telequipment DM53S oscilloscope used in Section 1 of PVER experiments (see pg. 136).

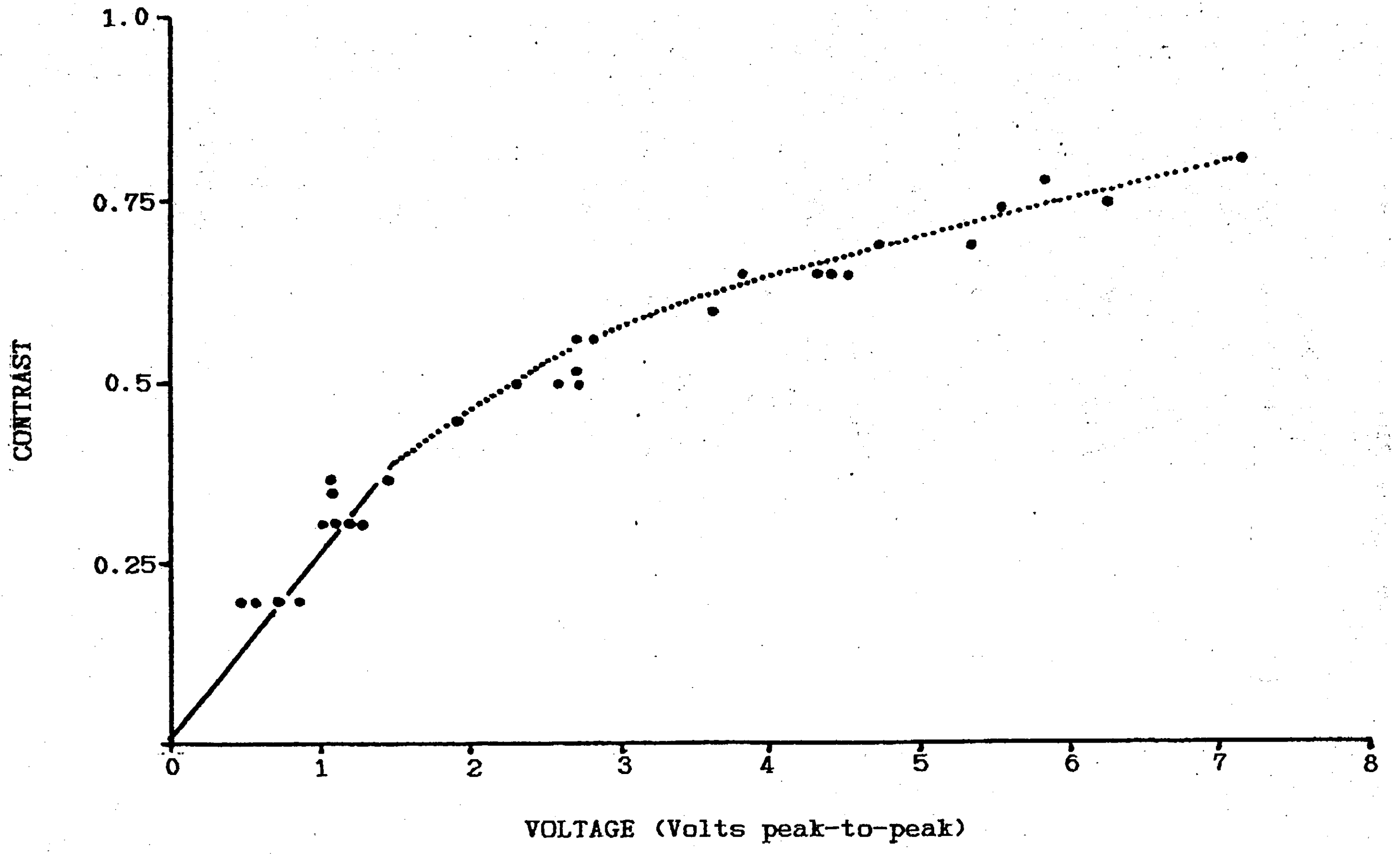

FIGURE 3. Relationship of grating pattern contrast to Z-modulation voltage for Tektronix 606B oscilloscope used in Section 2 of PVER experiments (see pg. 137).

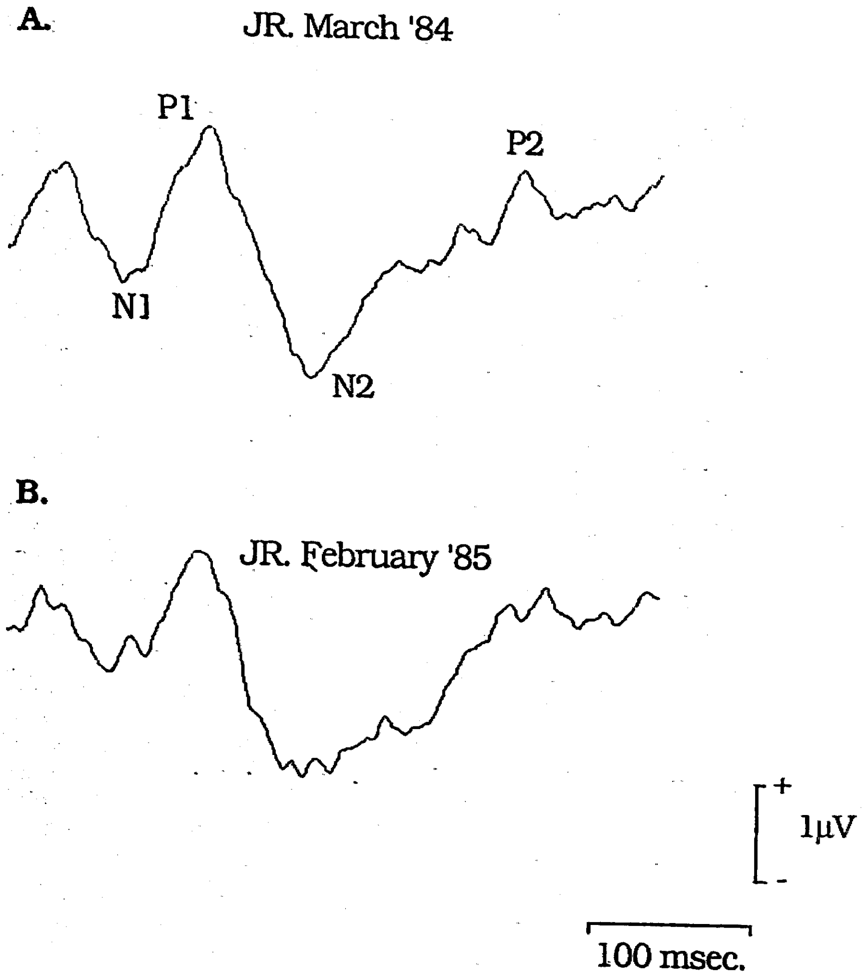

FIGURE 4. Reproducibility of the PVER to a grating pattern of 3 c/deg and 40% contrast; recordings dated as shown.

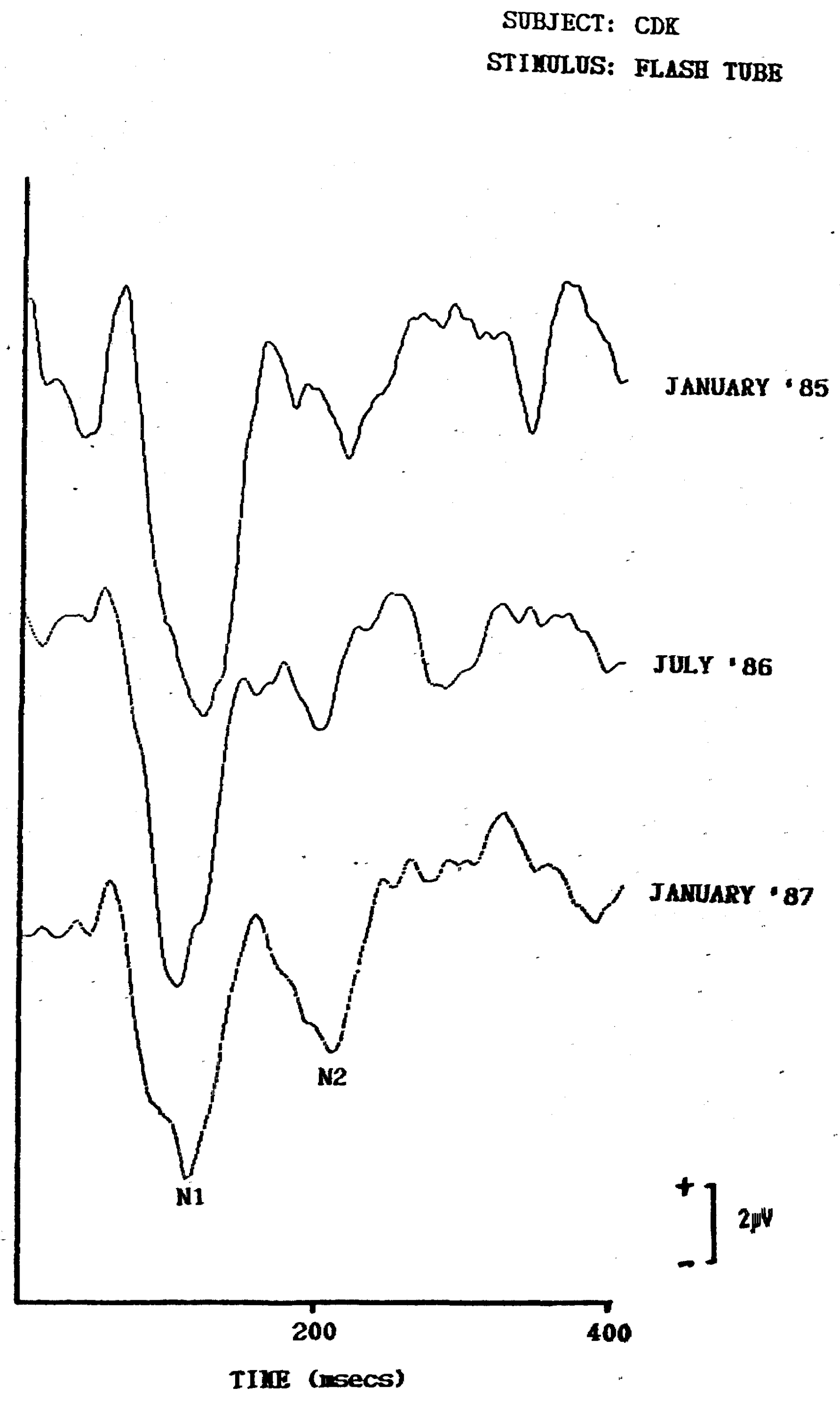

FIGURE 5. Reproducibility of the flash VER to a stimulus of intensity 1.0 x 10^7cd/m^2); recordings dated as shown.

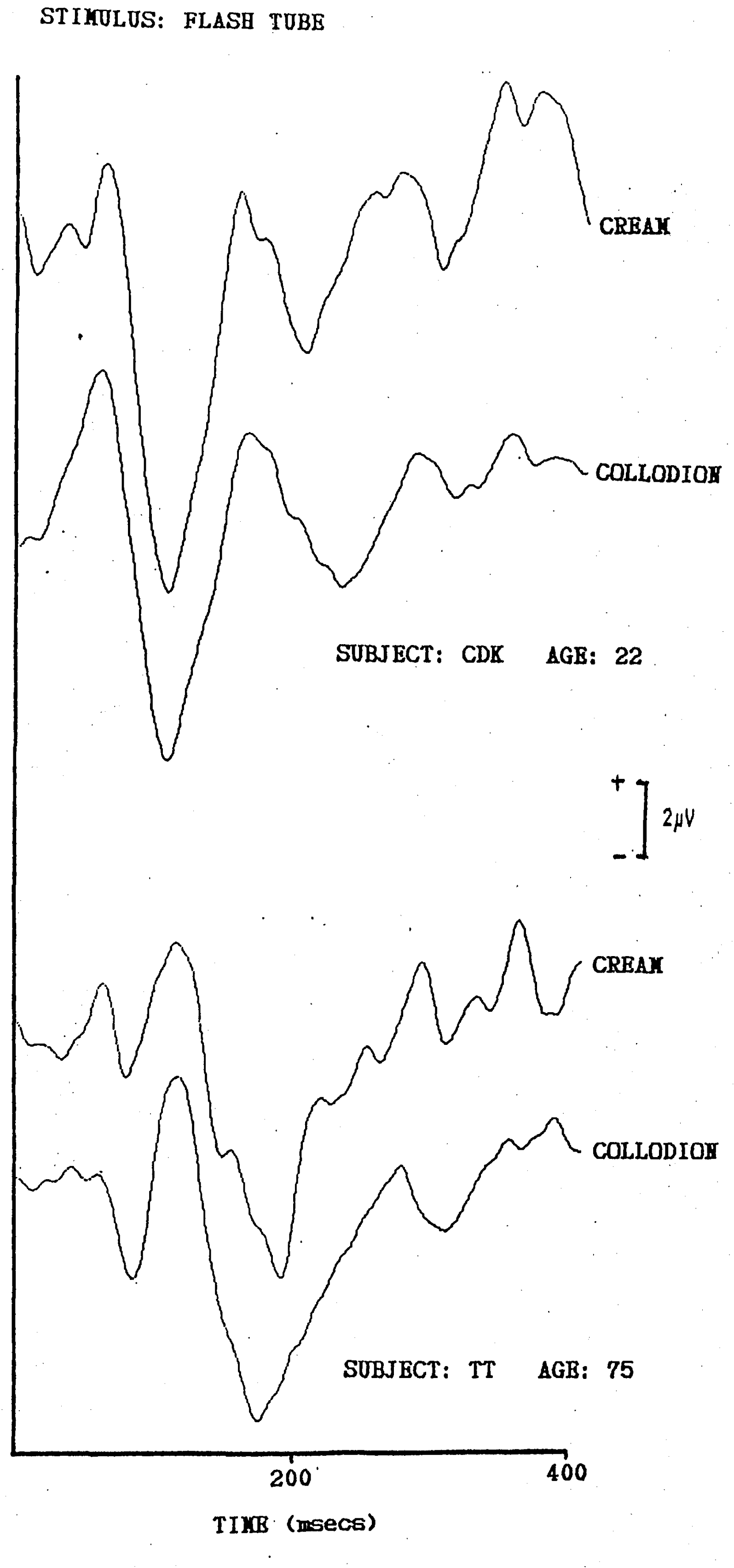

FIGURE 6. The effect on the flash VER of different adhesive media.

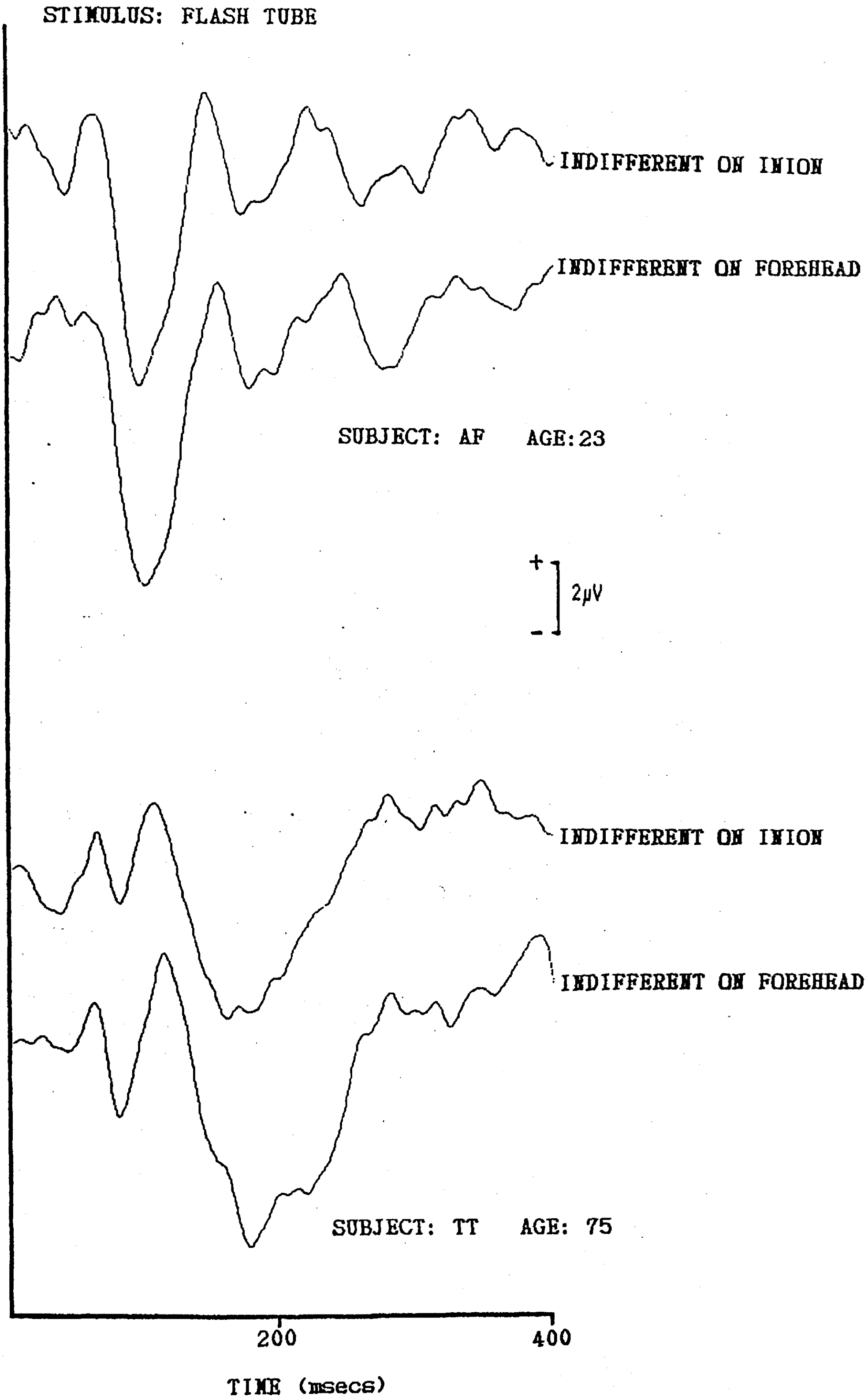

FIGURE 7. The effect on the flash VER of varying the position of the indifferent electrode.