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PARAMETRIC STUDIES ON PATTERN RECOGNITION MECHANISMS IN HUMAN VISION

BY

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ABSTRACT

In this thesis, I have examined experimentally the response characteristics of visual mechanisms which mediate pattern discrimination. The dependence of the response time, for the detection of a target on the number, N, of reference elements, from which it differed by a single parameter, provided a measure of the extent to which the target could be discriminated by parallel operations. In the first set of experiments, the data established that discrimination of orientation and magnification is dependent on the complexity of the reference field. Discrimination required longer search times when the reference field was composed of equal numbers of two classes of reference element than when it was composed of a single class, the two classes being themselves differentiated by the same parameter as that which distinguished the target.

In the second set of experiments, I examined sensitivity to colour differences and to difference in contrast polarity, and I show that the mechanisms responsible for discrimination of both orientation and magnification are selectively sensitive to both stimulus parameters. There are residual interactions between patterns of opposite contrast polarities and also between those of different colours, and the latter persist under equiluminance conditions.

In the third set of experiments, I have investigated the interactions between orientation and magnification in making discriminations. I determined that mechanisms for discrimination of orientation are tuned to the magnification of the elements, whereas those which mediate discrimination of magnification are relatively insensitive to orientation.

In the fourth set of experiments, I examined luminance discrimination and found that response times are relatively

faster for low luminance than for high luminance reference elements.

In the last set of experiments, I studied discrimination with complex elements, which were constructed by incorporating circles with the simple elements used in the previous experiments. The results show that times for detection of such complex elements are longer than those for the corresponding simple elements when the circles enclose the simple element, but not when the circle is within the simple element.

In the final chapter, I summarize my results and conclusions, and propose a hierarchical model for the visual mechanisms which mediate the discriminations described in the thesis.

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CHAPTER ONE

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1. Introduction:

The eye is Man's window to the outside world. It was thought at one time that the eye is the instrument which can distinguish different objects from each other. It is now well known, however, that the eye is just an instrument that refracts the picture of the world around us onto the retina, which in turn transmits it through neuronal pathways to the brain, so that the brain can analyse this picture and give it meaning, colour and direction. To be able to understand how this system works, it is important first to discuss the anatomy of the visual pathways.

1.1. Anatomy of the Eye and The Visual Pathways:

The eyes are one of the five types of sense organs in the human being. Each eye has a layer of photo-sensitive receptors, and a system of nerves for conducting impulses from the receptors to the brain. The principal structure of the eye is shown in Fig 1-1. The outer protective layer of the eye ball, the sclera, is modified anteriorly to form the transparent cornea, through which light rays enter the eye. The light rays then enter the crystalline lens via the anterior chamber. The crystalline lens is a transparent structure held in place by a circular lens ligament (zonule). In front of the lens is the pigmented and opaque iris, the coloured portion of the eye. The iris contains circular muscle fibres that constrict and radial fibers that dilate the pupil. The diameter of the pupil can vary to produce up to sixteen-fold changes in the amount of light reaching the retina.

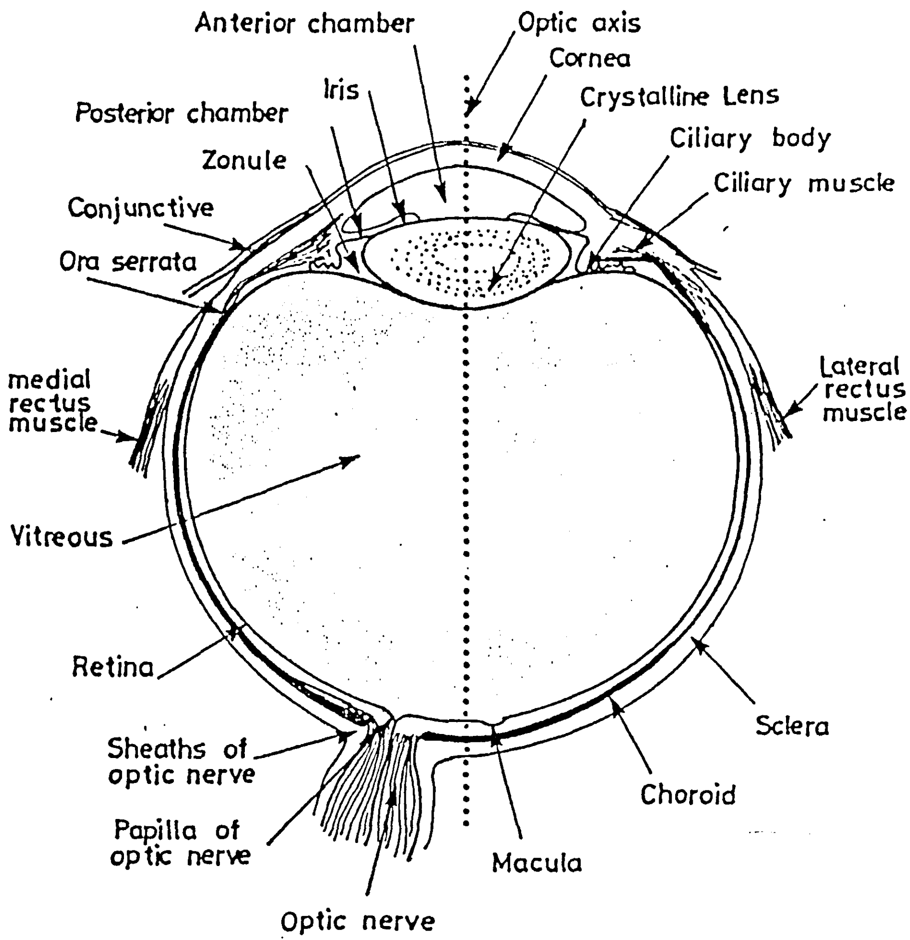


FIG. 1-1. Section of the right eye in horizontal plane, (After Eycleshymer and Jones, 1945).

1.1.1. The Retina:

Lining the sclera from inside is the choroid, then the retina. The choroid is a pigment layer that contains many of the blood vessels which nourish the structure in the eye ball. The retina is the neural tissue containing the receptor cells. It extends anteriorly almost to the ciliary body. It is organized in 10 layers and contains the rods and cones which are visual receptors, plus five types of post-receptoral neurons; bipolar cells, ganglion cells, horizontal cells, amacrine cells and the more recently discovered interplexiform cells (Fig 1-2).

The space between the lens and the retina is filled primarily with a clear gelatinous material called the vitreous humor.

The rods and cones, which are located next to the choroid, synapse with ganglion cells. The axons of the ganglion cells converge and leave the eye as the optic nerve. Horizontal cells connect receptor cells to other receptor cells via a feed-back loop in the outer plexiform layer. Amacrine cells connect ganglion cells to one another in the inner plexiform layer and in some instances may be inserted between bipolar cells and ganglion cells. They have no axons, and their processes make both pre- and postsynaptic connections with neighbouring neural elements. The interplexiform cells are post-synaptic to the bipolar cells and are pre-synaptic to the horizontal and bipolar cells and therefore feed signals backwards from the inner to the outer plexiform layer. Since the receptor layer of the retina is opposed to the choroid, light rays must pass through the ganglion cell and bipolar cell layers to reach the rods and cones. The pigmented layer of

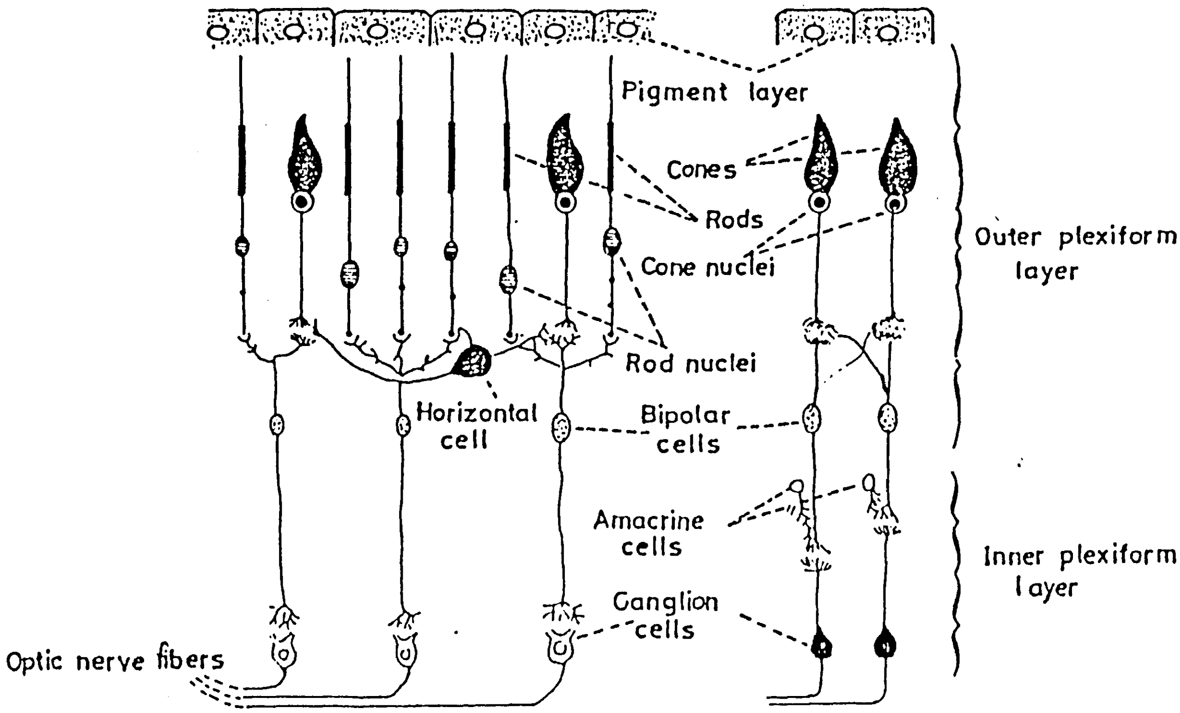


FIG. 1–2. Neural organization of the retina, peripheral area to the left, foveal area to the right.

choroid next to the retina absorbs light rays preventing the reflection of rays back through the retina. Such reflection would produce blurring of the visual images.

The blind spot is at a point 3mm medial to and slightly above the posterior pole of the globe. It is called the blind spot because there are no visual receptors overlying this spot. At this spot the optic nerve leaves the eye and the retinal blood vessels enter it. This region is visible through the ophthalmoscope as the optic disk. At the posterior pole of the eye, there is a yellowish pigmented spot, the macula lutea. This marks the location of the fovea centralis, a thinned out, rod-free portion of the retina where the cones are densely packed and there are very few post receptoral cells and no blood vessels overlying the receptors. The fovea is highly developed in humans. It is the point where visual acuity is greatest. When attention is attracted to or fixed on an object, the eyes are normally moved so that light rays coming from the object fall on the fovea.

1.1.2. The Primary Visual Pathways:

The visual field can be divided into two parts, the right side and the left side. The right visual field is focused in the left half of the retina, the left visual field is focused in the right half of the retina. The impulses from each eye leave the retina by the optic nerve. The fibres of the optic nerve reach the optic chiasm, where the signals coming from the right side of the retina of both eyes pass through the right optic tract. Consequently the signals coming from the left side of both retinae pass through the left optic tract. The signals then reach the lateral geniculate body, a part of the thalamus. Axons of geniculate neurons form the geniculocalcarine tract, which passes to the occipital lobe of the cerebral cortex. Each geniculate body contains six well defined layers, and on each side layers 1, 4 and 6 receive input from the contralateral eye, whereas layers 2, 3 and 5 receive input from the ipsilateral eye. As a result, the right half of the the visual field is processed by the left hemisphere and the left half by the right hemisphere (Fig 1-3).

1.2. Electrophysiology of The Visual System:

Transduction of light by photoreceptors leads to the generation of electrical signals, which are transmitted through the retina via chemical synapses. The direct transmission pathway is from photoreceptors via bipolar cells to the ganglion cells, but these parallel pathways are interconnected by the horizontal and amacrine cells.

1.2.1. Rods and Cones:

Rods and cones are the two types of photoreceptors, differentiated by their shape. Each human retina contains about 125 million rods and 5.5 million cones: yet only some million optic nerve fibers lead from the retina to the brain. Thus, an average of 125 rods plus 5 to 6 cones converge on each optic nerve fiber. However, there are major differences between the peripheral retina and the central retina, for nearer the fovea, fewer and fewer rods and cones converge on each optic fiber, and the rods and cones both become slenderer. These two effects progressively increase the acuity of vision towards the central retina. In the very central portion, in the fovea, there are no rods at all. Also the number of optic nerve fibres leading

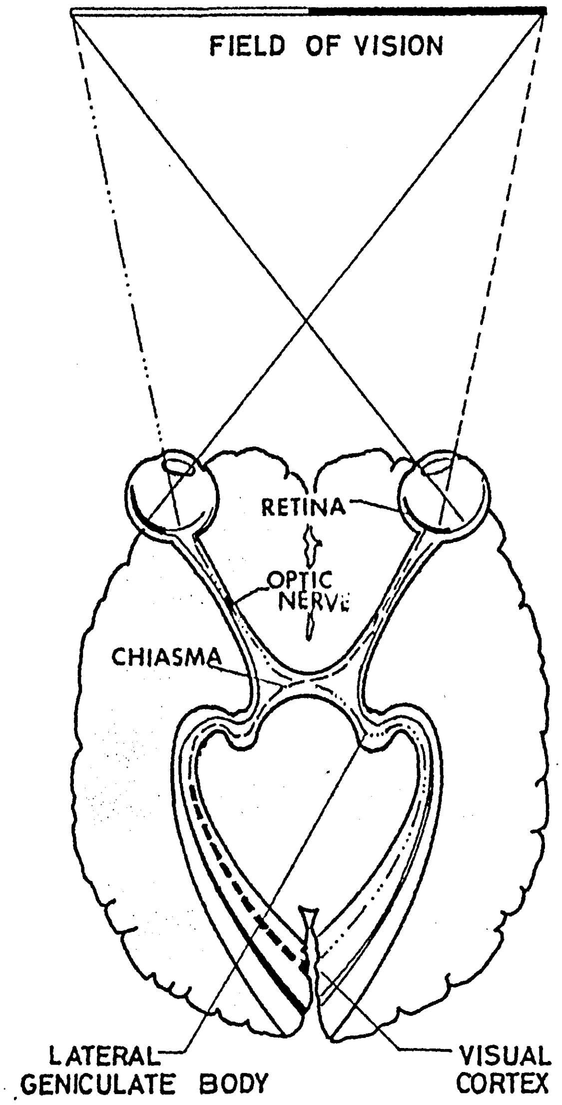


FIG. 1-3. The organization of projection fibres from the retina to the visual cortex. Note that fibres from the left side of both retinae - representing the right side of the visual field - project to the left hemisphere and that fibres from the right side of both retinae - representing the left side of the visual field - project to the right hemisphere. (From Rock, 1984).

from this part of the retina is almost equal to the number of cones. This mainly explains the high degree of visual acuity in the central portion of the retina in comparison with the very poor acuity in the peripheral portion.

Another difference between the peripheral and central portions of the retina is the considerably greater sensitivity of the peripheral retina to weak light. This results partly from the fact that as many as 300 rods converge on the same optic nerve fiber in the most peripheral portions of the retina; the signals from the rods summate to give intense stimulation of the peripheral ganglion cells. But in addition, rods are more sensitive to weak light than are cones, because of intrinsic differences in the receptors themselves (see Table 1-1). Therefore, rods are responsible for night vision (scotopic vision) and cones are responsible for bright light vision (photopic vision) and for colour vision.

Table 1-1. The Physiological differences between Rods and Cones. (Ripps and Weale, 1976).

	Rods	Cones
Operating Conditions	dim light	daylight
Sensitivity	high	low
Spatial Resolution	poor	good
Temporal Resolution	poor	good
Maximum Sensitivity	blue-green	yellow-green
Directional Sensitivity	slight	marked
Rate of Dark Adaptation	slow	fast
Colour Vision	absent	present

1.2.2. Pre-Ganglion Cells:

The various types of cells connecting the photorecptors to the ganglion cells are the bipolar cells, the horizontal cells and the amacrine cells. The bipolar cells have post-synaptic contact with the photoreceptors and horizontal cells and pre-synaptic contact with the amacrine and ganglion cells. Microelectrode recordings from the retina of fish (Kaneko, 1970, 1971; Naka, 1977) and mudpuppy (Werblin and Dowling, 1969) indicate that the receptive field of the bipolar cell is concentrically organized into two antagonistic zones, "on" centre and "off" surround and "off" centre and "on" surround. Bipolar cells are divided into three groups, rod bipolar which is connected to rods, flat bipolar and midget bipolar both connected to cones. In humans, there is a further subdivision of bipolar cells at the fovea, which are extremely small and have one-to-one contact with the cones (Dowling and Boycott, 1966).

Horizontal cells make lateral synaptic contact with photoreceptors and bipolar cells in the human retina (Kolb, 1970). The important feature of the horizontal cells is that their axons extend laterally over large areas of the retina. In primates, two types of horizontal cells have been identified, type A making dendritic connections with only cones and type B with only rods (Boycott and Dowling, 1969). Both bipolar cells and horizontal cells are amplitude modulated, and they respond to light stimulation in a graded manner rather than by means of an action spike, (Rodieck, 1973).

Studies on amacrine cells (Kaneko, 1970; Werblin and Dowling, 1969) reveal that the characteristic response of amacrine cells is a transient depolarization to a light flash or to a moving spot, from which may arise a regenerative all-or-none action spike. The amacrine cells are interneurones responsible for lateral connection in the retina (Cajal, 1893; Dowling, 1968; Boycott and Dowling, 1969). They synapse with bipolar and ganglion cells.

1.2.3. The Ganglion Cells:

The axons of ganglion cells transmit information to the brain in the form of spike potentials, and these are the final retinal output. The ganglion receptive field is roughly circular in outline and contains two zones, a centre and a surround. The response of illuminating each zone is quite different (Fig 1-4). A spot of light in the centre of the field causes an increase in firing rate for 'on' centre receptive fields and a decrease for 'off' centre receptive fields, while an annulus of light in the surround causes the firing rate to decrease for 'on' centre receptive fields and increase for 'off' centre receptive fields. The response can be divided into two principal functional groups, regardless of the nature of the central response ("on" or "off"), known as X-type and Y-type. X-type cells give linear interactions between concentric centre and surround region, and they tend to have smaller receptive fields than the Y-type ganglion cells, which give non-linear interactions between centre and surround regions (Enroth-Cugell and Robson, 1966). A further division of ganglion cell responses can be made on the basis of their temporal characteristics, as some yield sustained signals during stimulation whilst others give transients at stimulus 'on' and/or 'off', with little sustained activity. X-type ganglion cells tend to give sustained responses and Y-type tend to

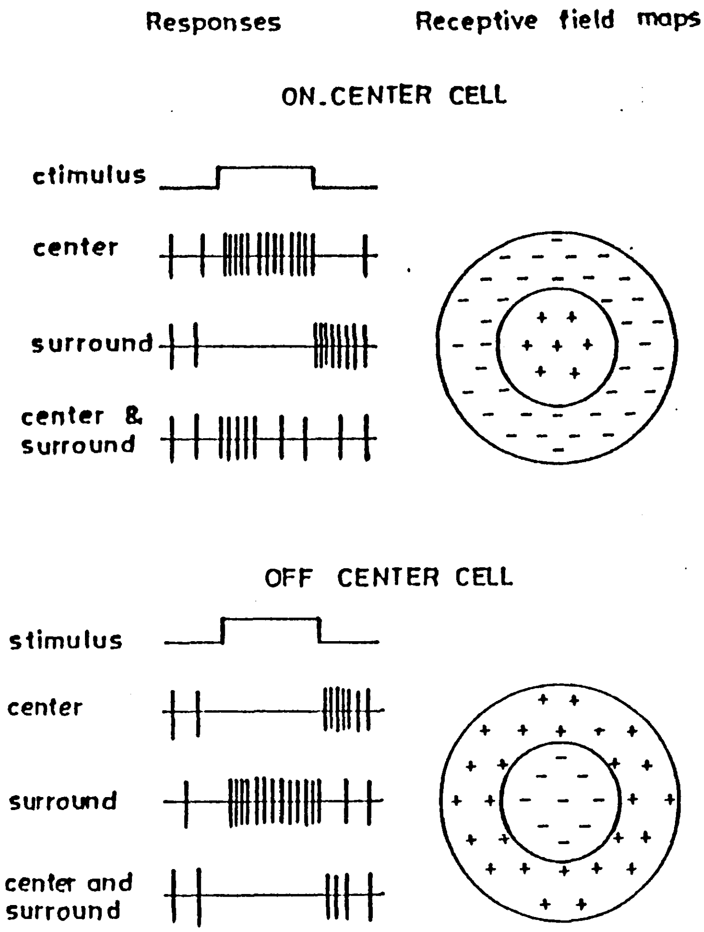


FIG. 1-4. Idealized responses and receptive field maps for on-centre (top) and off-centre (bottom) contrast-sensitive ganglion cells. The drawings on the left represent hypothetical responses to a spot of light presented in the centre of the receptive field, in the surround of the receptive field, or in both the centre and surround regions of the receptive field. '+' symbol on the receptive field map indicates an increase in the firing rate of the cell, that is, excitation; '-' symbol indicates a decrease in the firing rate, that is, inhibition. [From Dowling, 1987].

give responses with strong transients at stimulus onset and cessation, but there is overlap in these temporal characteristics between the two groups (De Monasterio, 1978a). Most X-type ganglion cells are colour coded so that centre and surround receive signals from different cone types. Y-type cells conduct signals along their axons more quickly than X-type cells and there is evidence (in cat, Rodieck, 1973, Stone and Fukuda, 1974; in monkey, De Monasterio, 1978b) that there is a third type of ganglion cell, W-type, which conducts signals slower than X-type cells. In primates, both X and Y-type ganglion cells project to the LGN, whereas Y and W-type cells project to the mid-brain.

1.2.4. The Lateral Geniculate Body:

The receptive fields of cells in the LGN are similar to those of ganglion receptive cells in that they also have centre and surround sensitivity. Wiesel and Hubel (1966) distinguished three types of cells in the four dorsal layers in the rhesus monkey. Type I cell, the most common, has an excitatory or inhibitory centre and an opponent surround, the centre and surround having different spectral sensitivities. They also showed opponent-colour responses, giving on-responses to one set of wavelengths, off-responses to another set, and no response at some intermediate wavelengths. In the dark-adapted state, some of these cells behaved as though they had no connections with rods, while others showed clear evidence for rod input. Type II cells, a small minority, lacked any centre-surround receptive-field arrangement, but gave opponent-colour responses over all regions of the receptive field. These cells behaved as though they received opponent inputs from two sets of cones with identical distributions over the retina. Two types were seen:

green-on, blue-off, and green-off, blue-on. A few cells seemed to have opponent connections with green and red cones. In dark adaptation these cells showed no evidence of rod connections. Type III cells had concentrically arranged on-centre or off-centre receptive fields, the centre and surround having identical spectral sensitivities regardless of wavelength. Only two of the four types of these cells receive inputs from rods to both centre and surround, in opponent fashion, when dark adapted.

The LGN projection to the visual cortex is topographically organized. The geniculocortical projection is different in mammalian species. In the opossum, hedgehog, mouse and in primates, the LGNd projects to area 17 (Wilson and Cragg, 1967; Valverde, 1968; Hall, 1970; Benevento and Ebner, 1971). In the cat the laminae project to areas 17 and 18, and the medial interlaminar nucleus (MIN) projects to area 19, as assessed from retrograde degeneration (Garey and Powell, 1967; Niimi and Sprague, 1970). Lesions in the LGN give rise to multiple areas of fibre degeneration in areas 17, 18, 19 and in the middle suprasylvian gyrus (Wilson and Cragg, 1967; Garey and Powell, 1971; Rossignol and Collonier, 1971). Other studies show that the chief projection of the main laminae is to areas 17 and 18 (Graybiel, 1970, 1972; Heath and Jones, 1970; Jones, 1972). Livingstone and Hubel (1982) showed by cytochrome-oxidase injections into the monkey's LGN that there is a clear projection of LGN fibres into the primary and secondary visual cortex.

1.2.5. The Visual Cortex:

All layers of the lateral geniculate body relay visual information to the visual cortex through the geniculo-calcarine tract. The ability to detect spatial organization of the visual scene, that is, to detect the form of objects, brightness of the individual parts of the objects, shading, and so forth, depends on function of the primary visual cortex. The visual cortex can be subdivided into two major zones (Fig 1-5), the striate and the prestriate cortex.

1.2.5.a. <u>The Striate Cortex:</u>

The primary visual cortex V1 (Brodmann's area 17) or striate cortex receives most of the visual input from the eye through the LGN. The visual hemifield is completely mapped onto the contralateral striate cortex, a proportionately larger amount of cortex being devoted to the fovea than to peripheral retina. Most of the cells in the striate cortex possess elongated receptive fields, and respond selectively to bar or edge shaped stimuli, and are responsive to contours of specific orientation and width (Hubel and Wiesel, 1962, 1968). The cells in this area were categorized as simple, complex and hypercomplex by Hubel and Wiesel. Simple cells are stimulated by long narrow rectangles of light (slits), straight-line borders between areas of different brightness (edges), and dark rectangular bars against a light background. The orientation of the receptive field axis required for maximum response varies from cell to cell. Receptive fields for complex cells, unlike those for simple cells, did not respond to light as predicted from the arrangements of excitatory and inhibitory regions. Otherwise, optimum response for stimuli is just like that of simple cells. It differed from simple fields in that a stimulus was effective wherever it was placed in the field, provided that the orientation was appropriate. Hypercomplex cells are distinguished by their selectivity to

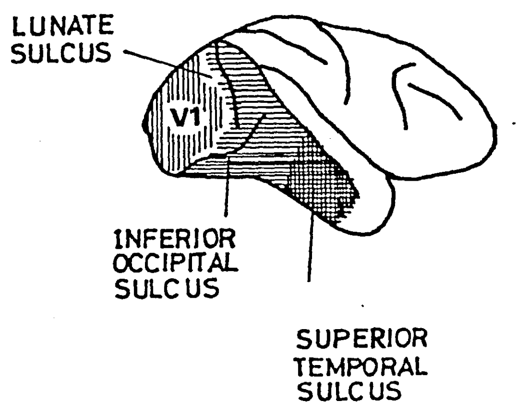


FIG. 1 _5. Lateral view of the right hemisphere of the brain of rhesus monkey. The striate cortex (VI-vertical stripes) is situated posteriorly and ends 2 mm behind the lunate sulcus on the lateral side. The prestriate cortex (horizontal stripes) lies in front of the lunate sulcus and includes the depths of the deep sulci. Its anterior boundary is uncertain and it merges into the superior temporal cortex (cross hatched) which is known also to have a visual function (after Zeki, 1978).

stimulus length, but extending the line beyond the activating part of the receptive field in one or both directions causes a marked decrease in response. Subsequently, doubt has been cast on the existence of this third hypercomplex group of cells (Schiller, et al., 1976) and it now seems probable that they correspond to the group of non-orientated cells with colour selective responses, discussed below.

Hubel and Wiesel (1968) have also divided the striate cortex of macaque and spider monkey into two independent systems of columns extending vertically from the surface of the brain to the white matter. Columns of the first kind contain cells with common receptive field orientations. In the second type, cells are aggregated into columns according to eye preference. An organisation corresponding to the cortical layering was also observed, with the cells grouped in such a way that simple cells were found mainly around the middle layers (layers III, IVA and IVB) while complex and hypercomplex cells were found primarily in the upper and lower layers (layers II, the upper two thirds of III, V and VI).

Inputs from the two eyes are brought together in the striate cortex. Colour opponent cells have also been found in layer IVB in foveal striate cortex (Gouras 1974). The majority of the cells in this layer do not show orientation or directional selectivity, but in layers further away from IVB the cells become more sensitive to orientation and direction. In general the orientation sensitive neurones are not selective in their response to wavelength; Michael (1978) has, however, reported cells selective to both orientation and colour. There are highly specific projection patterns from VI to other cortical areas (Zeki, 1988).

1.2.5.b. <u>The Prestriate Cortex:</u>

Anterior to the striate cortex, and surrounding it, is another cortical region, of different cytoarchitectural design, known as the prestriate cortex. The striate cortex projects to the various areas of prestriate cortex (Fig 1-6). The prestriate cortex is divided into six different areas, all of which, except the motion area of the superior temporal sulcus (V5) (Shipp and Zeki, 1985), lie within Brodmann's cytoarchtectonic area 18. Each of these areas has distinct anatomical inputs, separate callosal connections and carries a separate, distinctive and topographical map of the visual field.

Most cells in V2 and V3 are orientation selective (Zeki, 1978) while V3 cells have larger receptive fields than V2 cells (Zeki and Sanderman, 1976; Van Essen and Zeki, 1978). Cells in areas V3 and V3A have similar receptive fields and are mostly orientation selective, but are differentiated in that each has a distinctive map of the visual field and distinctive anatomical inputs and callosal connections which make them independent visual cortical areas.

Lying lateral to V3A in the lunate sulcus, and extending on to the prelunate gyrus, and then the lateral part of the posterior bank of the superior temporal sulcus, is area V4 complex (Zeki, 1971) (Fig 1-7). This part of the prestriate cortex contains heavy concentrations of colour coded cells (Zeki, 1973, 1975), a low percentage of orientations selective cells and an increase in the number of colour biased cells (Zeki, 1978, 1980).

V5 is the motion area of the superior temporal sulcus

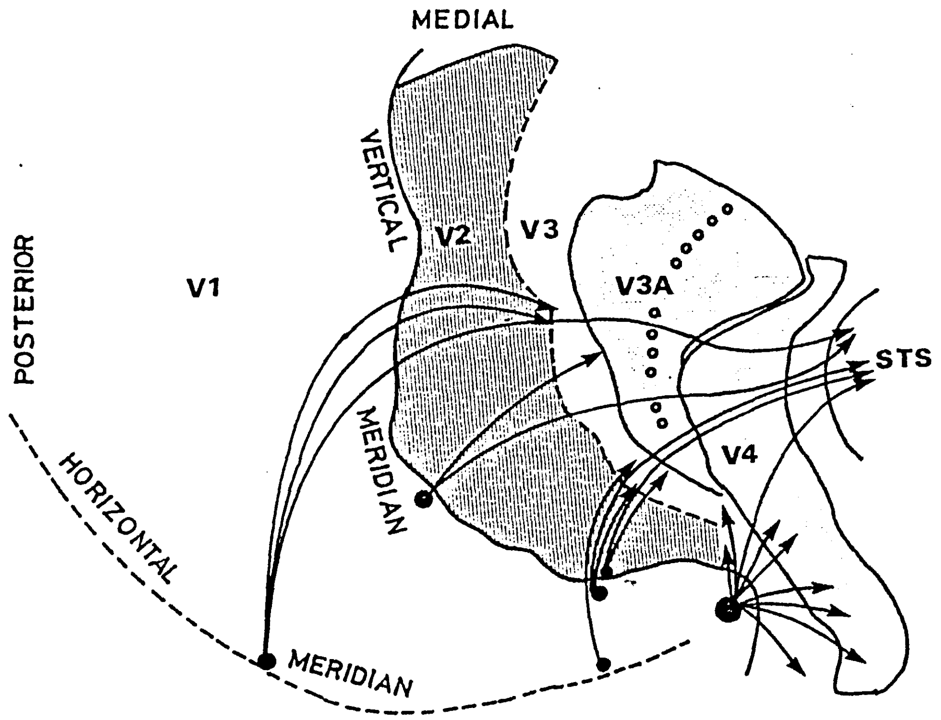


FIG. 1 _ 6· Diagram showing the projections of the striate cortex, displayed on a 'flattened out' striate and prestriate cortex. Only the projections of the part of the striate cortex representing lower visual fields are shown, but the part of the striate cortex representing upper visual fields has similar projections. Interrupted lines indicate the representation of the horizontal meridian and continous lines that of the vertical meridian. Note that each part of the striate cortex has direct projections to V2, V3 and the medial part of the posterior bank of the superior temporal sulcus (STS). The region of the striate cortex at which the centre of the gaze is represented has an additional projection (from Zeki, 1978).

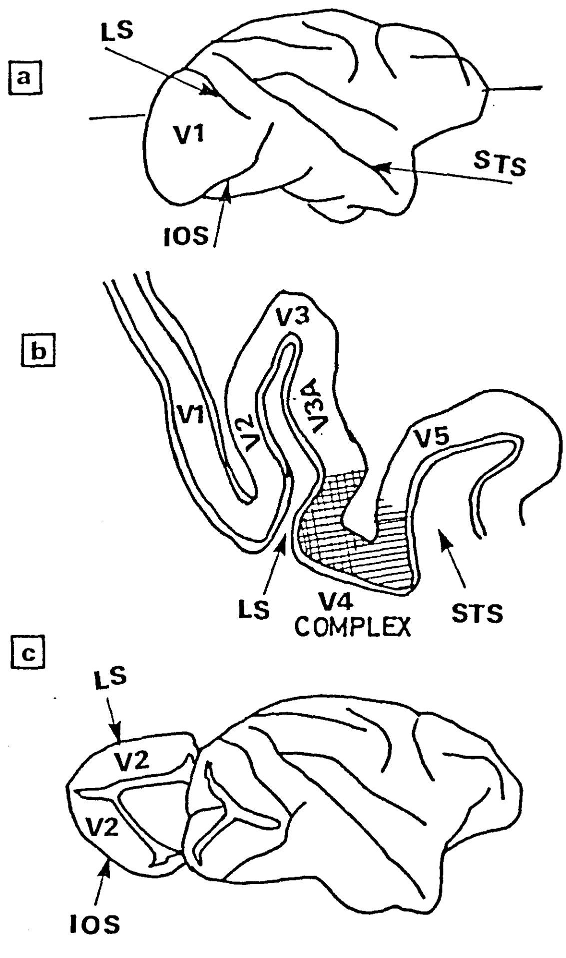


FIG. 1 _7. Drawings of: (a) the surface of the left hemisphere of a macaque monkey brain; (b) the lateral part of a horizontal section, taken at the level indicated in (a) to show the locations of the prestriate areas V2 to V5. The V4 complex (hatched) consists of at least two areas with further subdivisions in each; (c) illustration of how the occipital operculum is removed and showing the relation of V2 to V1. LS, lunate sulcus; STS, superior temporal sulcus; IOS, inferior occipital sulcus. (From Zeki, 1985).

much of which falls within Brodmann's cytoarchitectonic area 19. There is a total absence of wavelength-selective cells in area V5, most cells being directionally selective (Zeki, 1974 and 1983; Gattas and Gross, 1981), and responsive to the real motion of objects (Movshon et al., 1984) in the field of view (Newsome et al., 1985). Anatomical evidence shows that cells in V1 projecting to V5 are not only segregated into separate layers but that, within each layer, they are separated from cells projecting elsewhere (Zeki, 1988).

Summing up the capabilities of the different areas in the prestriate, Fig 1-8 shows the percentage distribution of orientation selective, colour selective and directionally selective cells in V2, V3, V3A, V4, and superior temporal sulcus (V5).

1.2.6. Other Projection Pathways:

In the previous section, I talked about the primary visual pathway from the eye to the visual cortex via the LGN. In the next section I will discuss other visual pathways from the retina ganglion cells through the optic chiasm to the mid-brain.

1.2.6.1. Superior Colliculus (Optic Tectum):

The retina projects topographically upon the tectum (in cat: Laties and Sprague, 1966; Garey and Powell, 1968), and a given region of each retina can influence a local region of the tectum by one or both of two routes, through the retinotectal pathway, or via the LGNd and visual cortex. There is a map of the visual field on the superficial layers of the monkey superior colliculus, the scaling of which is similar to that

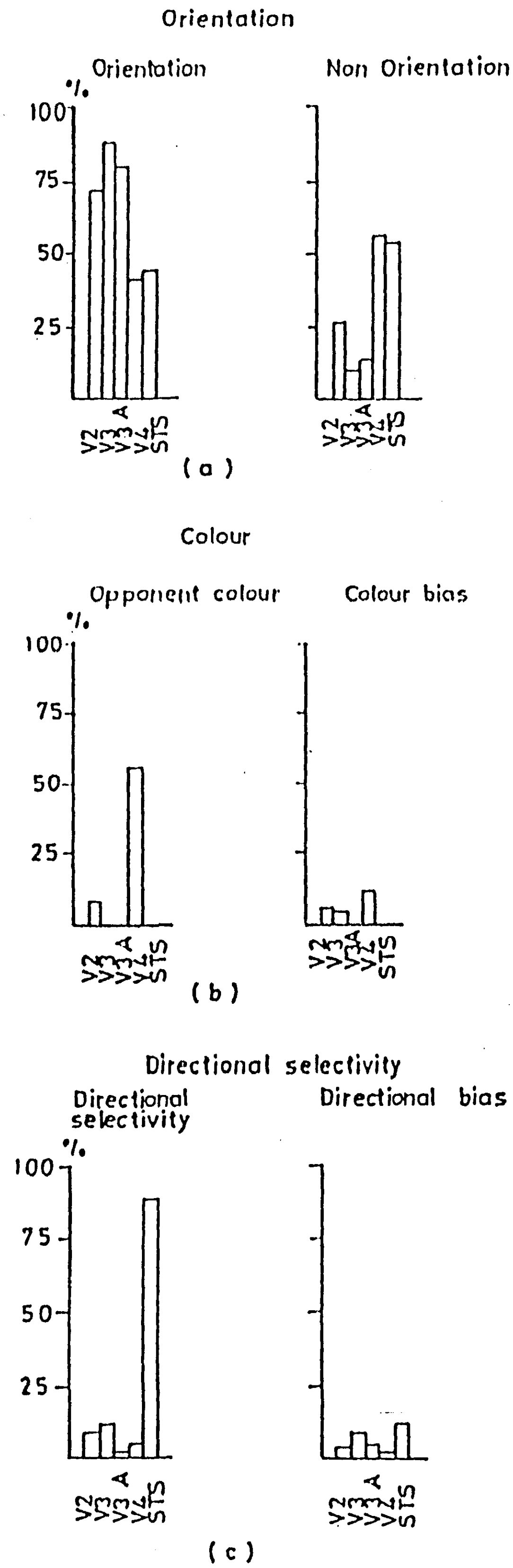


FIG. 1-8. The percentage distribution of orientation and non-orientation selective (a), colour selective (b) and directionally selective (c) cells in the prestriate area. (from Zeki, 1978).

observed on the striate cortex (Cynader and Berman, 1972; Goldberg and Wurtz, 1972).

Other studies on cat superior colliculus (Hoffmann, 1972, 1973) show that the superior colliculus receives strong input from two major classes of retinal ganglion cells, 11% of the Y (large-soma cells) and 89% of the W (small-soma cells) (Fig 1-9) and no input from X-class (medium-soma cells) ganglion cells. Actually there are three projections from the retina to the superior colliculus: fast direct, involving the direct projection of retinal Y cells; slow direct, involving the direct projection of retinal W cells; and fast indirect, involving the relay of Y-cell activity to the superior colliculus via the dLGN and visual cortex. It was also found (Hoffmann and Sherman, 1974, 1975) that monocular deprivation has little effect on the Y-direct and W-direct pathways to the superior colliculus, but severely weakens the Y-indirect pathway, and binocular visual deprivation seemed to leave unaffected the direct-W component of the retinal input to the superior colliculus, but to weaken both the direct-Y and the indirect-Y components.

Retinocollicular projection in the monkey is similar to that of the cat. The superior colliculus receives input form Y- and W-ganglion cells, and not from X-cells (Schiller and Malpeli, 1977; Leventhal et al., 1981). Marrocco (1978) reported that 9% of the retinal input to the superior colliculus comes from fast-axon ganglion cells and 91% from slow-conducting afferents.

In the rat studies (Sefton, 1969; Fukuda, 1977; Fukuda and Iwama, 1978) showed that there are three conduction velocity groups present among optic tract axons, and

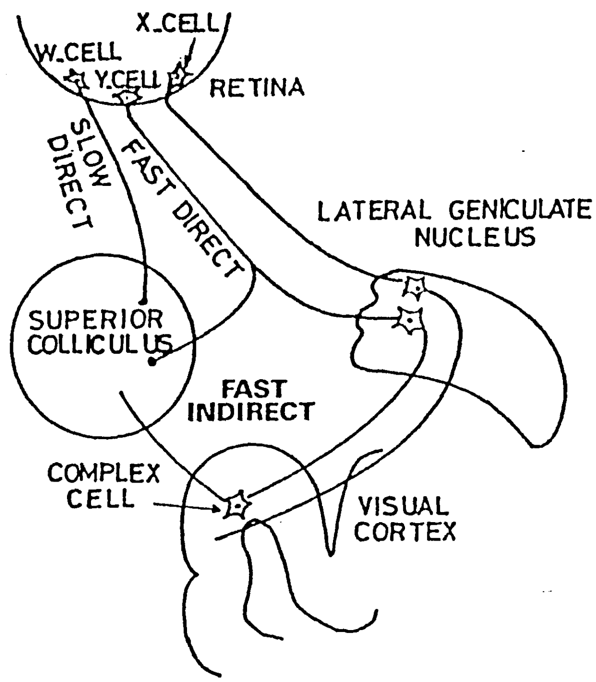


FIG. 1-9. Hoffmann's 1973 model of three pathways from the retina to the superior colliculus in the cat. W-cells with slow conducting axons project directly to the superior colliculus (SC); fast-conducting Y-cells axons branch to the LGN and the SC; and Y-class relay cells in the LGN activate 'complex' cells in the visual cortex, which send their axons to the SC. (Form Stone, 1983).

evidence indicates that each group branches to reach both the LGN and the superior colliculus.

1.2.6.2. <u>The Pulvinar:</u>

Evidence has been reported of a weak but direct retinal input to the inferior pulvinar of two primates, the rhesus monkey and baboon, but not in the squirrel monkey or bush baby (Campos-Ortega and Hayhow, 1970). Electrophysiological studies of Ohno et al. (1975) provided evidence of retinal input to the pulvinar of the tree shrew, via slow conducting optic nerve axons.

The projection from the retina to the retinal-recipient zone of the pulvinar is topographically organized, and the cells of the retinal-recipient zone are relatively small, about the size of W-class relay cells. The ganglion cells that project to the pulvinar have fine axons and appear to be medium-soma cells (Leventhal et al., 1980). Some of the cells in the retinal-recipient zone have receptive field properties characteristic of retinal W cells (Mason, 1981).

There is a well established projection of the pulvinar to the striate and prestriate cortex and to the inferotemporal lobe (Orgen and Hendrickson, 1977). The functional importance of the retinal-recipient zone of the pulvinar is not known however; perhaps it should be regarded as part of the LGN.

1.2.6.3. <u>The Pretectal Area:</u>

The pretectal area of the mid-brain is interposed between the tectum and thalamus. This area receives input from the retina. The ascending connexions of the pretectum are to the pulvinar region of the thalamus

(Graybiel, 1972), taking part in the extrageniculate relay to the cortex. The visual cortex sends descending connections to the pretectum and nucleus of the optic tract (Garey and Powell, 1968; Heath and Jones, 1970).

1.3. Psychophysical Methods for Studying the Visual System:

Sight is one of the five senses of man. Methods used to study the performance of this sensory system directly and quantitatively are called psychophysical methods. These non-invasive methods can be used to study the organisation of vision in man and to assess functional disturbance of visual function.

I will therefore review some of the psychophysical methods which are related to the experiments discribed in this thesis. These measurements are obtained by presenting visual stimuli to an observer and measuring the responses as a function of the stimulus parameters.

1.3.1. Increment Threshold Measurements:

The technique for measuring the increment threshold requires a target, usually a spot of light of variable luminance, flashed on a background field of fixed luminance, and the luminance at which the spot of light is no longer detected is determined. In Fig 1-10 the threshold luminance of the test spot, $\triangle I$, is plotted against the background field luminance, I, on which it is superimposed. The graph shows that at low background luminance levels, the test luminance has a constant value for detection, and this is attributed to the noise in the visual system and is sometimes called 'dark light'. At higher background field luminance, the test spot luminance is directly proportional to the background field luminance, i.e. $\triangle I \propto I$.

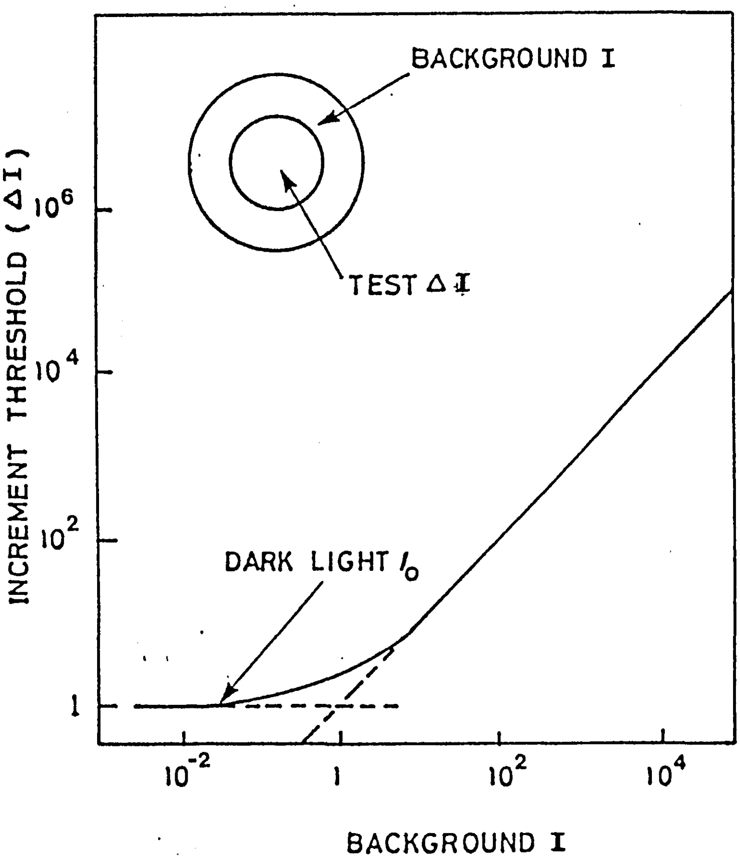


FIG. 1 - 10. The effect of background luminance on the detection of a superimposed, flashed stimulus. (After Aguilar and Stiles, 1954).

1.3.2. Two Colour Increment Threshold and Colour Matching Measurements:

The simplest method of showing that colour vision is trichromatic is by matching a test colour against a mixture of three matching stimuli. This method has been reviewed many times (e.g. Wright, 1946) and forms the basis of the international colour standard Commission International d'Eclairage. The chromaticity chart for the 2 deg. standard observer is used in Chapter Two to specify the coloured stimuli used in this investigation.

The two colour increment threshold technique was developed by Stiles (1939, 1949, 1959) to separate the cone mechanisms and investigate their properties. It involves measuring the threshold for a small test stimulus, presented in flashes and foveally fixated, on a much larger adaptation field. The test stimulus and the adapting field are monochromatic lights of different wavelengths, λ and μ respectively. Increment threshold luminance, U_λ , for detection of a flashed target of wavelength λ, is measured as a function of the luminance W_μ of a background field (Fig 1-11). The response breaks into several components, each of which has the same shape and each of which is associated with a different spectral response or π mechanism. In a second version of the experiments, threshold for a target of, say 0.5 log unit luminance, is determined by increasing the background luminance until the test target is no longer seen. Measurements with a fixed target wavelength, λ, and for different background wavelengths, μ, yield spectral response functions. Such measurements were performed for different wavelengths of the test target and yield spectral response curves which describe the mechanism responsible for detection

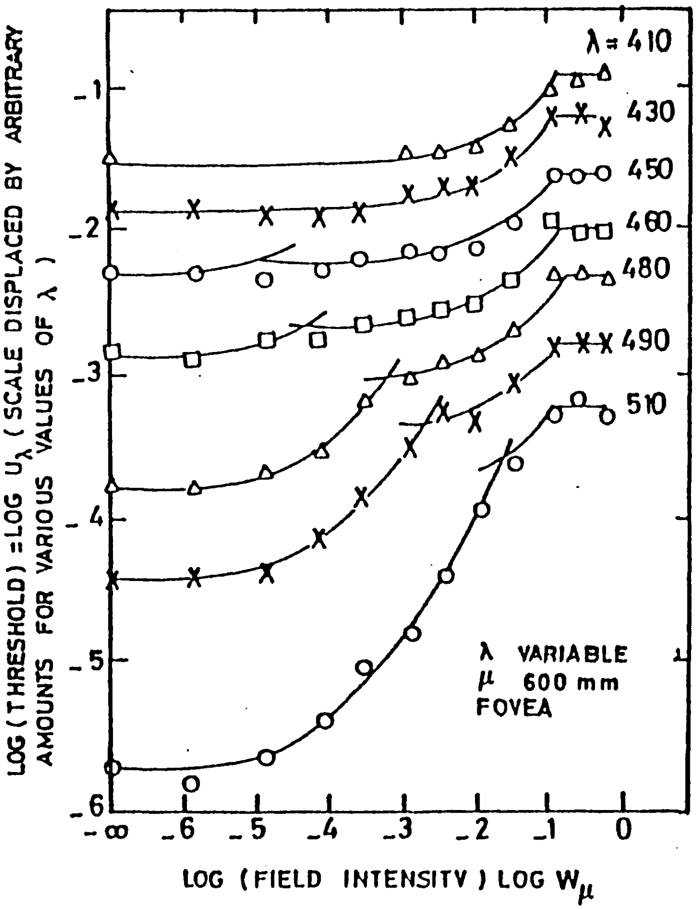


FIG. 1-11. The effect of varying test wave lengths, λ, on threshold luminance, U_λ, for a background of fixed wavelength, μ, equal to 600 nm and luminance W_μ. The curves have been given arbitrary displacement along the U_λ axis. The short horizontal part of the curves at high intensities is attributed to Π_3, the branch below this to Π_1, and the lowest branch, which does not appear for λ = 410 and 430 nm, to Π_4. The mechanisms have different test sensitivities and thus are relatively displaced along the axis of U_λ, but the branch corresponding to any one mechanism has always the same shape and same position on the scale of W_μ. (From Stiles, 1949).

of the target. By these methods, Stiles found three spectral sensitivity curves which were blue sensitive (π_3, maximum sensitivity near 440nm), green sensitive (π_4, maximum sensitivity at 540nm) and red sensitive (π_5, maximum sensitivity between 570 and 590nm), (Fig 1-12). Stiles found two more spectral responses for the blue sensitive mechanism, called π_1 and π_2, two for high background illumination π_4' and π_5', and one for the rod response, π_0.

1.3.3. Spatial and Temporal Vision:

Our eyes enable us to recognise and discriminate the shapes of objects around us; the accuracy with which this is performed gives us a measure of the spatial resolution of the visual system. Our eyes also respond to detection of movement, which is a simple example of temporal pattern analysis.

For the clinical testing of spatial resolution, visual acuity, a Snellen letter chart is commonly used. It consists of a series of dark letters of decreasing size, on a bright background. The smallest letters that are correctly identified give a measure of the acuity. The gaps between individual components of the letters subtend 1 min at a specified viewing distance, and each complete letter then subtends 5 min of arc. The acuity is recorded as a fraction, the numerator being the testing distance and the denominator the distance at which the gaps would subtend 1 min of arc.

The Snellen chart measures spatial resolution at high contrast and frequency, but, to measure resolution for a wide range of spatial frequencies, contrast sensitivity for a one-dimensional sinusoidal grating is measured. The contrast of the grating is defined as $(I_{max} - I_{min})/(I_{max} + I_{min})$, where I_{max} and I_{min} are

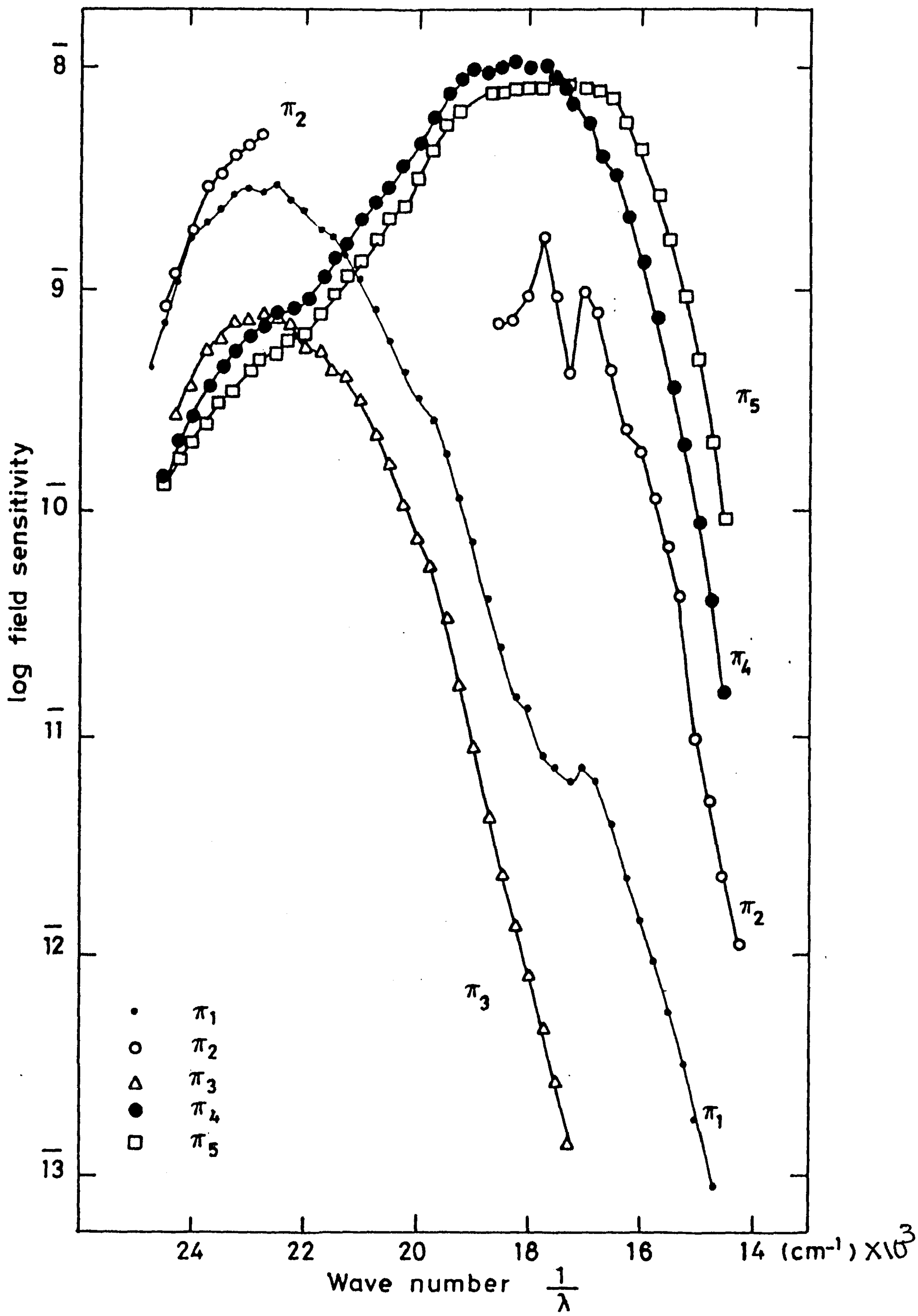


Fig 1–12 Experimental values for some of the π–mechanisms, given by Stiles (1939, 1949, 1959). Sensitivity for detection of a monochromatic target is plotted against the inverse of the target wavelength, λ.

the maximum and minimum illumination levels respectively. The contrast threshold at which a sinusoidal grating can just be detected provides a description of spatial response (Fig 1-13).

The temporal characteristics of the stimulus are defined by the duration of a single flash, by the temporal frequency (in Hertz) of a sinusoidal modulated stimulus, or by the periodicity of any other periodic waveform. A good example of a temporal response is the critical fusion frequency (CFF), defined as the frequency at which flicker can just no longer be detected in a fully (100%) modulated stimulus (Fig 1-14). A more comprehensive description of temporal response is provided by the modulation transfer function of the visual system (Fig 1-15).

1.3.4. Spatio-temporal Channels:

The transmission of signals from the eye to the brain involves both spatial and temporal filtering of visual signals. The electrophysiological data for retinal ganglion cells suggest that more than one class of filter is involved in the transmission process.

To investigate these channels, threshold illumination for detection of a target moving across a structured background with a variety of different spatial and temporal parameters was studied, with the background of illumination kept constant for each set of data. Two types of visual mechanisms were found (Barbur and Ruddock, 1980; Holliday and Ruddock, 1983), one with high spatial frequency and low-pass (sustained) temporal response, ST1, and the other with low spatial frequency and band-pass (transient) temporal response, ST2.

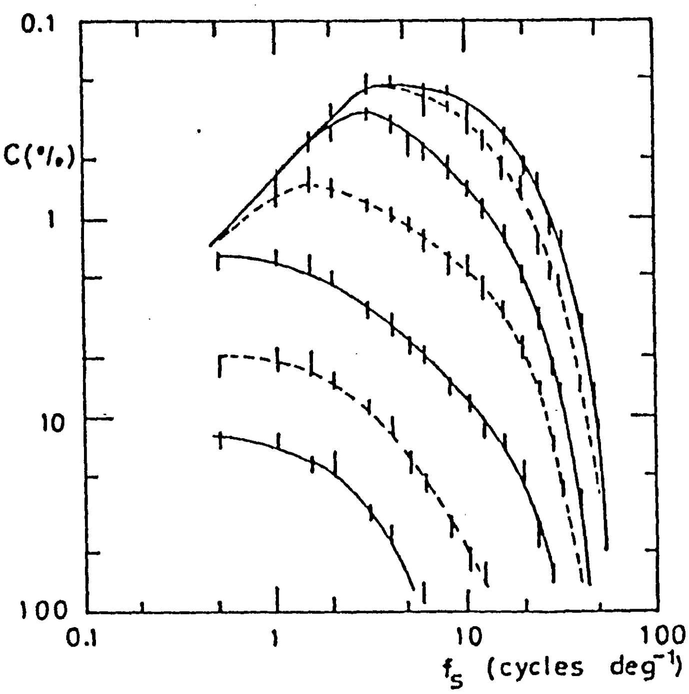


FIG. 1-13. The contrast level C, defined as $(I_{max}-I_{min})/(I_{max}+I_{min})\times 100\%$ required for detection of sinusoidal grating of spatial frequency f_s. Each curve refers to a different mean illumination, I_o, increasing in steps of x10 from 0.0009 trolands (upto 900 trolands) from lower left to upper right. (After Van Nes and Bouman, 1976).

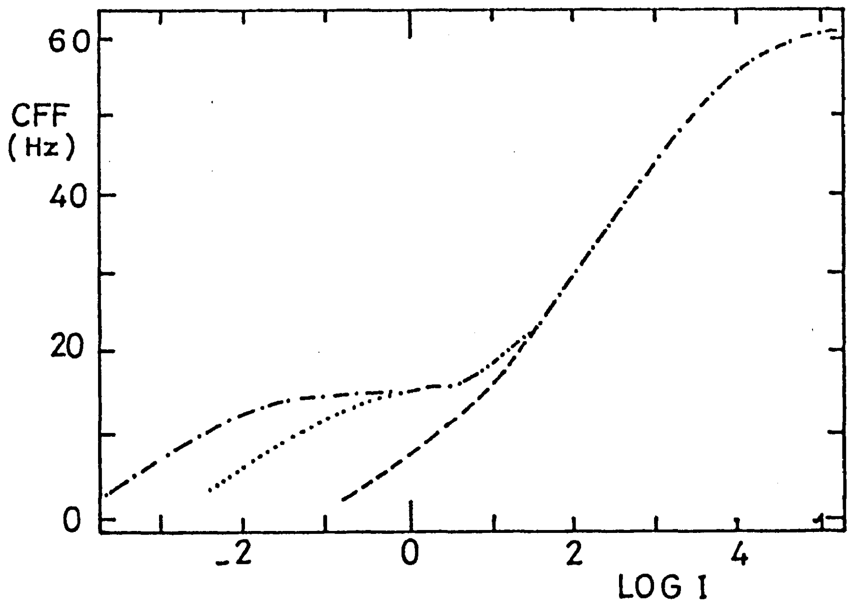


FIG. 1 -14. Critical fusion frequency (CFF) plotted as a function of retinal illumination I (log troland) for a circular field (diameter 19°). At lower illuminations, different stimulus wavelengths yield different values according to their effectiveness in stimulation of the rod system (450 nm -. -. -.; 575 nm .... and 670 nm ----). (After Hecht and Schlaer, 1936).

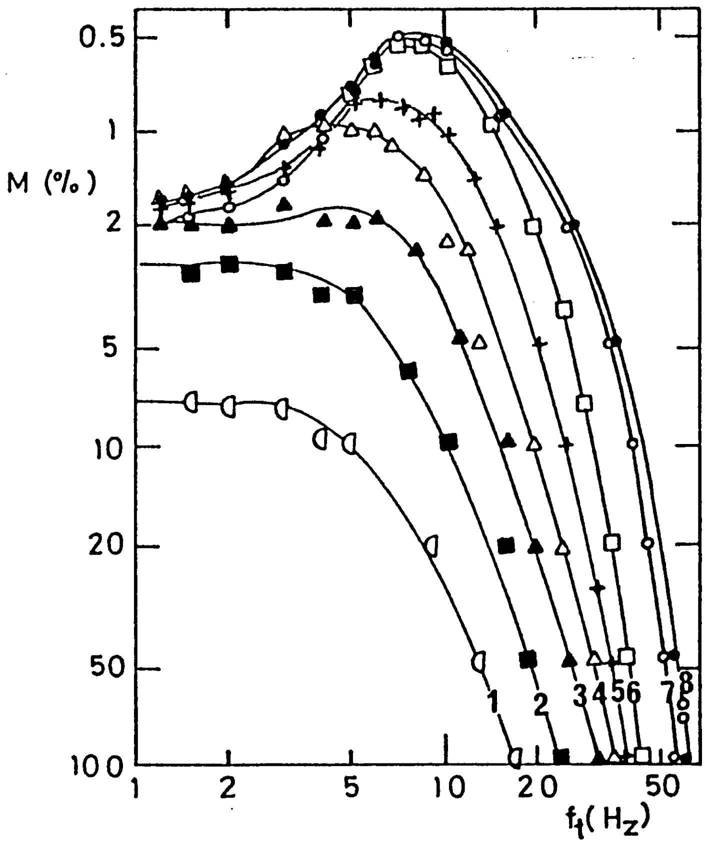


FIG. 1 — 15 . Modulation depth (%) required for detection of sinusoidal flicker of frequency f_t in a small circular field (diameter 2°) on a large surround (diameter 60°). Each curve refers to a different mean illumination, I_o, increasing from 0.375 (1), 1(2), 3.75(3), 10(4), 37.5(5), 100(6), 1000(7) to 10,000 trolands (8), (After de Lange, 1958).

1.3.4.1. Spatio-temporal (ST) 1 Channel:

a. Spatial Responses:

The spatial characteristics of this channel were obtained by measuring threshold illumination for detection of a circular target moving across a square-waveform background grating (Fig 1-16a,b). Two spatial response curves were found (Barbur and Ruddock, 1980); one detects the target at lower background illumination and the other at higher background illumination. The background grating orientation does not have any effect on the frequency response curve, which implies that the channel has a radially symmetric spatial response. The amplitude of the response curve is linearly related to the contrast of the background grating. Fig 1-16c show typical data for the spatial frequency response.

Results showed that as the target size increases the response amplitude increases, but the frequency distribution is the same. Similar results were obtained for target velocity, but at low velocities the response characteristics were distorted.

b. Temporal Responses:

In order to investigate the temporal response, the background was constructed from two square waveform gratings, arranged in spatial antiphase and alternated at temporal frequency f_t (Holliday and Ruddock, 1983) (Fig 1-17a). At high temporal frequencies, the two component gratings fuse together and give a uniform background, while at

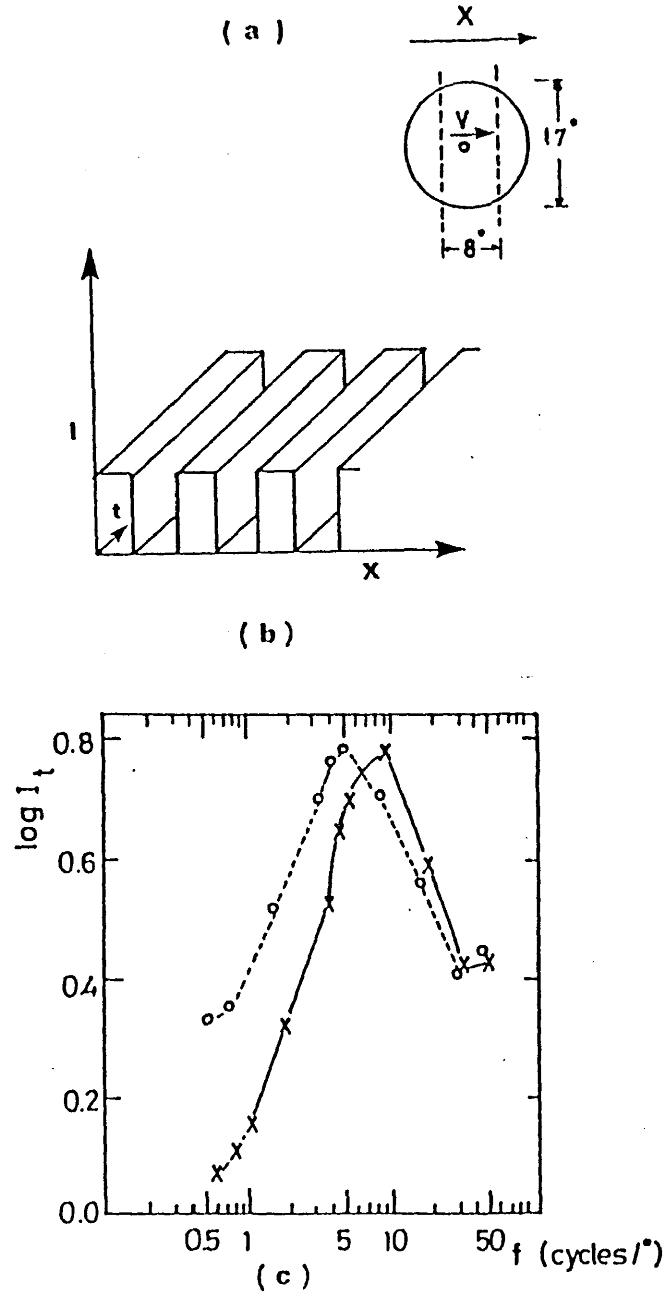


FIG. 1-16. (a) The configuration of the visual field, with the target moving at fixed velocity, V, across the ciruclar background field.

(b) Background field stimulus used to measure the STI spatial response with luminance, I, plotted against position, X and time, t.

(c) STI spatial response. Log threshold luminance, log I_t, for detection of the target, is plotted against f_i, the periodicity of the background grating, for mean background luminance of 1.4 log troland (circles) and 3.4 log trolands (crosses). (After Ruddock, 1983).

low temporal frequency, each of the gratings acts independently and corresponds to a single steady grating. Threshold illumination for detecting the moving target is measured as a function of the temporal frequency when the background field gratings alternate. The data (Fig 1-17b) exhibit low-pass response characteristics, with increased band-width at higher illumination levels.

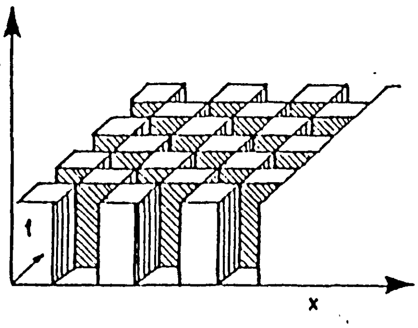
1.3.4.2. Spatio-temporal (ST) 2 Channel:

a. Spatial Responses:

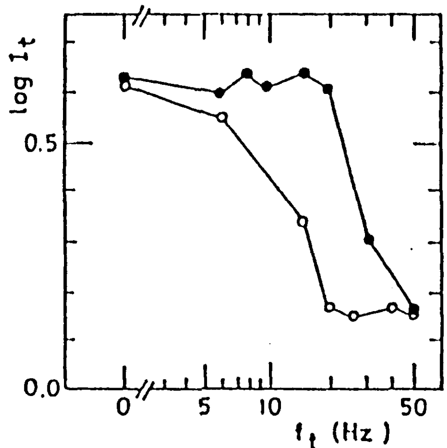
The background consisted of a grating of alternate steady and flickering bars (Fig 1-18a). The average luminance of the flickering bars was set equal to that of the steady bars, which provides a spatially modulated flickering background (Holliday and Ruddock, 1983). Threshold luminance for detecting the target was measured for different widths of the grating bars. Results show that the spatial response curve peaks at around 1 cycle/deg. (fig 1-18b). The ST2 response curve is independent of background grating orientation, its amplitude increases with increase in background modulation but the relationship between the two parameters is not linear. The spatial characteristics for ST2 are significantly coarser than those for the ST1 mechanism. Variation of the target parameters size and velocity shows that for low velocity and small targets, detection of the target is mediated by the ST1 rather than the ST2 channel.

b. Temporal Responses:

Temporal response curves are obtained using a



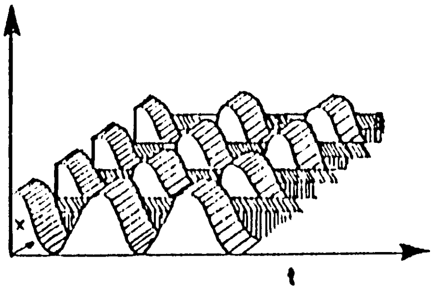
(a)



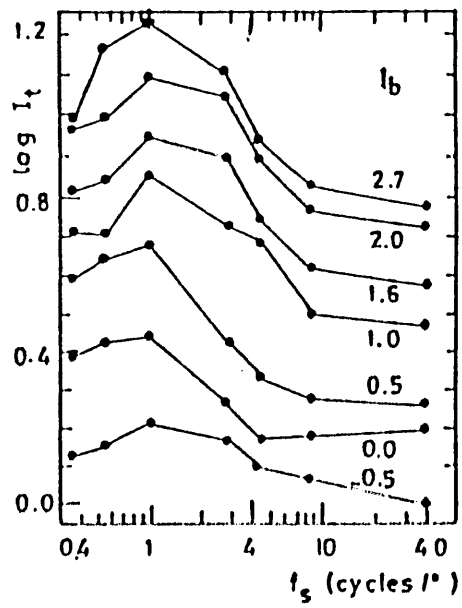
(b)

FIG. 1-17. (a) The illumination profile of the spatio-temporal modulated background used to measure the STI temporal response. Luminance, I, is plotted against position X and time t. The distribution corresponds to two gratings presented in spatial and temporal antiphase.

(b) The temporal response to the STI channel. The log threshold luminance, log I_t, for detection of the moving target is plotted against the temporal periodicity at which the two gratings are alternated. (After Ruddock, 1983).



(a)



(b)

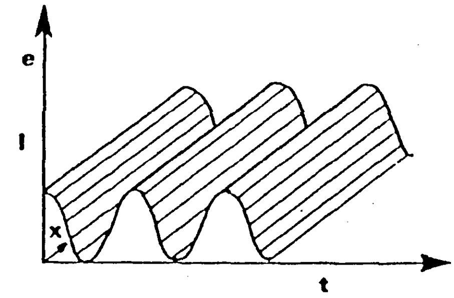
FIG. 1-18. (a) The background configuration used to determine the spatial response of ST2 channel. In this case the background consists of a spatially periodic grating which alternate between spatially steady and sinusoidally varying bars both sets of bars having the same average luminance.

(b) The ST2 spatial response. Log threshold illumination, log I_t, for detection of the varying target is plotted against the spatial periodicity of the alternating steady and flickering bars in the background. Values are given for a series of average background luminance, denoted in the Figure in log trolands. (After Ruddock, 1983).

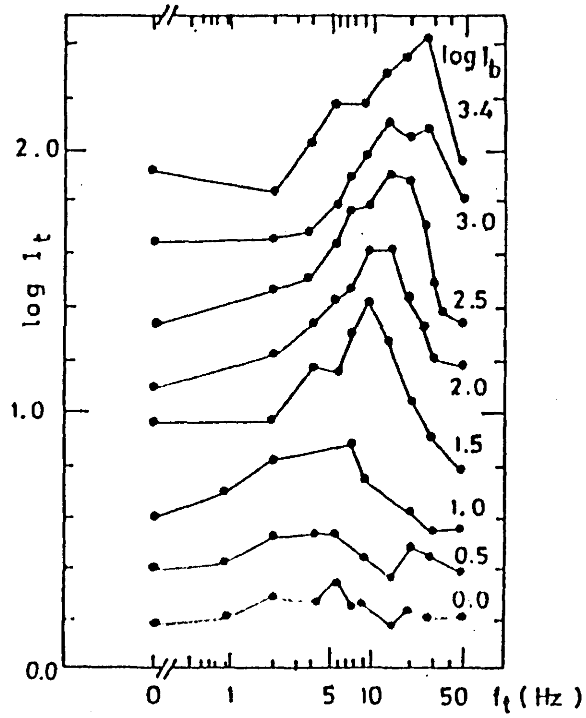
spatially uniform, temporally modulated background (Fig 1-19a) with a moving target. Threshold illumination for detection of the moving target is plotted against background flicker frequency (Fig 1-19b) and each curve refers to a different background luminance (Holliday and Ruddock, 1983). The ST2 temporal response is independent of target size and target velocity. The response curves are band-pass, and the frequency for maximum threshold luminance and the high frequency cut-off increase as background luminance increases.

1.3.5. Orientation Selective Spatial Responses:

The orientation sensitive mechanism in human vision can be demonstrated by the adaptation of the visual system to spatially structured stimuli. The first experiments of this kind were carried out by Gilinsky (1968), Pantle and Sekuler (1968) and Blakemore and Campbell (1969), and all used grating patterns as stimuli. Following adaptation to high contrast gratings, threshold contrast for detection of a test grating of spatial frequency and orientation similar to those of the adaptation grating is elevated. By changing the relative orientation or spatial frequency of the test and adaptation gratings, the specificity of the so-called contrast threshold elevation (CTE) effect can be determined. These phenomena are illustrated in Fig 1-20, and show that for a test grating of spatial frequency f_t, the frequency band width extends from $1/2f_t$ to $2f_t$, i.e. covers about two octaves, and the orientation tuning is about ±15 deg. Maudarbocus and Ruddock (1973b) showed that the spatial domain of the mechanisms with the measured spatial frequency response characteristics is equal to about one-bar-width of the test grating. They carried out their measurements with



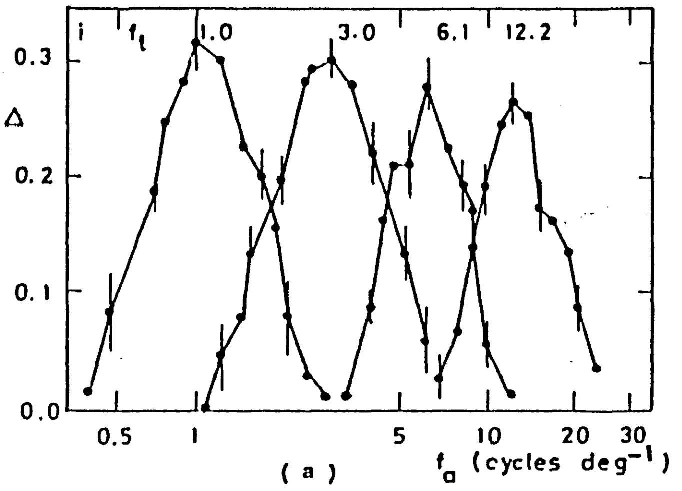
(a)

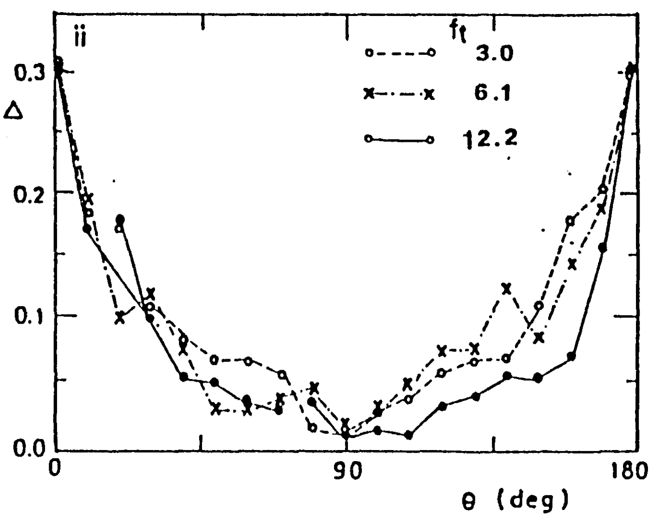


(b)

FIG. 1-19. (a) The luminance distribution of the background field used to determine the ST2 temporal response. This corresponds to a spatially uniform temporally modulated field.

(b) The ST2 temporal response. Log threshold luminance, log I_t, for detection of the target is plotted against the temporal frequency of the background field. Data are given for a number of average luminance of the background field as marked in log trolands in the Figure. (After Ruddock, 1983).





(b)

FIG. 1-20. Data for the orientation selective response channels revealed by adaptation methods. Adaptation effects, are presented in terms of Δ, the difference between log threshold luminance measured before and after adaptation.

(a) Spatial tuning curves measured for four vertically oriented test gratings of different spatial frequencies are marked on the Figure. Δ is plotted against the spatial frequency, f_a, of the adaptation grating to show width selectivity.

(b) The orientation selectivity curves measured for three different test gratings, with spatial frequency, f_t, oriented vertically. The adaptation gratings, in each case matched in spatial frequency to the test grating was oriented at angle θ to the vertical.
(After Maudarbocus and Ruddock, 1973b).

the test grating in one eye and the adaptation grating in the other, thereby showing that the effect arises in binocularly controlled mechanisms. Thus the responses are attributed to cortical stages of the visual system and have orientation specificity and spatial band width similar to those found electrophysiologically in simple cells of the cortex.

A second method is due to the demonstration of Blakemore and Sutton (1969), who showed that the apparent width of bars in a grating changes immediately after adaptation to a grating of different bar width, providing evidence of width and orientation selective visual mechanisms. Later Burton et.al., (1977) and De Valois (1977) established that the dark and light bars in the grating adapt independently of each other, i.e. there is an independent mechanism for positive contrast (light bars) and another mechanism of negative contrast (dark bars).

Extensive studies were performed to examine the band-width and orientation selectivity in relation to the length of the adaptation stimuli (Burton and Ruddock, 1978; Naghshineh and Ruddock, 1978; Ruddock, 1983). For the width selectivity, the effect was obtained by measuring threshold illumination for detection of the test grating as a function of the adaptation grating spatial frequency, the two gratings being oriented parallel to each other. Results obtained show that the threshold is maximum at an adaptation spatial frequency equal to that of the test.

The orientation selectivity of the response is also independent of the spatial frequency and of the orientation of the test grating.

For length selectivity, the threshold luminance for detection of a given test matrix was measured for a number of different test elements lengths. It was found that for longer test elements, the threshold increased with the increase in matrix length until saturation was reached, whereas for short test elements, threshold luminance is maximum when the adaptation length is equal to the test length, and falls for longer and shorter adaptation element lengths. The adaptation data here suggest that for longer test elements the receptive field along the axis can be considered a simple rectangle, of length to width proportions 3:1 (Fig 1-21) (Ruddock, 1983). This is similar to the electrophysiological results for simple cells in the striate cortex (Hubel and Wiesel, 1962, 1968). Results also show that the visual mechanism is tuned to within ±20 deg., and that it is binocularly driven (Ruddock et al., 1979) and non-selective in response to colour (Maudarbocus and Ruddock, 1973a).

1.3.6. Pattern Recognition:

Quantitative method for studying the visual performance in the discrimination of spatial patterns has been developed using simple geometric patterns (Foster 1984; Treisman, 1986; Ike et al., 1987). In Ike et al.'s study, the subject is asked to discriminate an element which differs from the elements of a reference field, consisting of a large number of identical elements, by a single parameter, such as orientation or magnification (Fig 1-22a). The discrimination time between presentation of the field and detection of the target is logged. The half time, $T_{\frac{1}{2}}$, required for discrimination of 50% of a given target is measured (Fig 1-22b). The probability of detection is investigated for various parameters such as

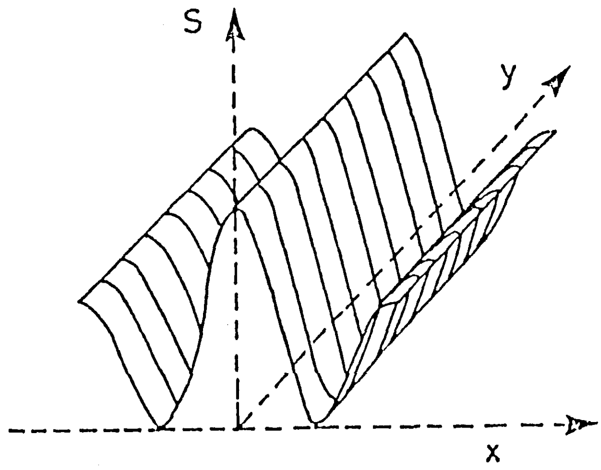
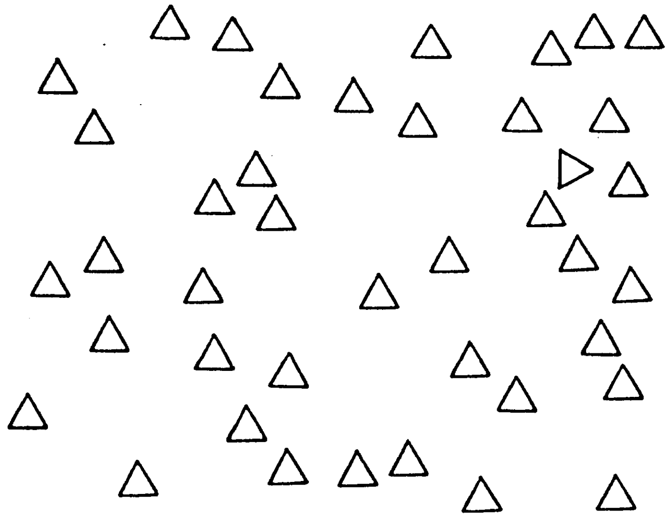
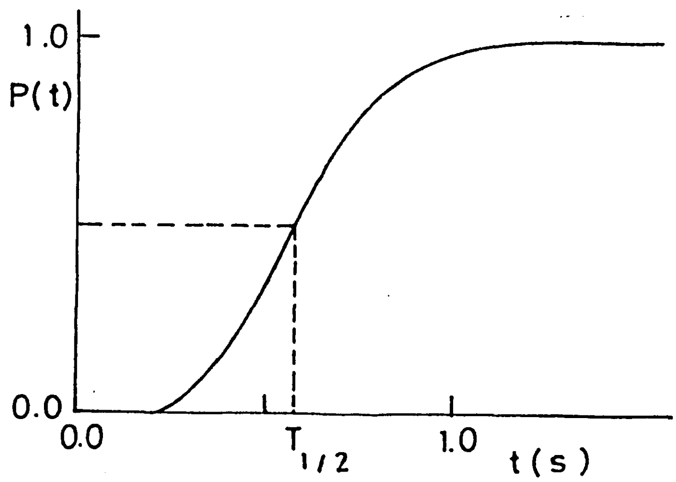


FIG. 1-21. The 2-D receptive field for non-length selective orientation selective mechanisms derived from psycophysical adaptation experiments. (From Burton and Ruddock, 1978).



(a)



(b)

FIG. 1-22 - a, b

(a) Example of a visual field for pattern discrimination measurements for orientation discrimination.

(b) Probability of detection, P(t), is plotted against the time of detection, t, and the time required for 50% probability of detection is marked.

magnification, orientation, texture, colour, luminance and contrast. The aim of this method is to understand the visual processing which contributes to such discrimination.

Ike et al.'s stimuli consisted of geometrical patterns, made up from spots and bars, and these were used to examine experimentally the visual processing of such elements. Several earlier experiments had provided strong evidence of the importance of line slope in primitive perceptual processes (Beck, 1966a, 1966b; Beck and Ambler, 1973; Atteneave and Olson, 1967). Atteneave and Olson (1967) showed that responses to vertical and horizontal lines or rectangles is faster than responses to these stimuli tilted 45 deg. to right or left. In 1968 Atteneave discovered the phenomenon of the ambiguous triangle, and showed that the equilateral triangles are "multistable" with respect to perceived orientation. A single equilateral triangle can be seen as pointing in any of three possible directions, but only one of them at a time. Palmer (1980) and Palmer and Bucher (1981) have looked into the configurational effects for the perceived pointing of ambiguous equilateral triangles, in an attempt to understand how they arise and what factors influence them. They proposed that configural effects arise from low resolution pattern information that influences the behaviour of the multistable system.

Ike et al. (1987) found that there are two mechanisms responsible for rotation discrimination; one responsible for orientation of lines and the other for orientation of pattern elements constructed from lines. Later it was found that changes in orientation or magnification of elements constructed of lines, could be distinguished by the visual system independently of the number of reference elements, i.e. by parallel processing. This holds till the differences in orientation or magnification become very small. Javadnia and Ruddock (1988a) found these limits to be about 8 deg. for orientation, 10% for magnification and about 5% for luminance, where the discrimination becomes serial. Treisman and Souther (1985) and Treisman (1988) suggested that the search becomes serial when the activity generated in the relevant feature map by the target and the distractors are more similar, and when the target appears to lack the relevant feature present in the distractor.

Visual illusions are another aspect of higher level processes in human vision, which are not clearly understood. Two hypotheses are given for the explanation of visual illusion, firstly that the identification of a specific pattern is carried out on the basis of available visual information, leading to misinterpretation of the image, and 'false images are produced, but it is not due to limitations of the brain (Gregory, 1963, 1966, 1968, 1970; Hoptopf, 1966). The second hypotheses is that visual illusion is due to distortion introduced during signal transmission along the visual pathways (Ginsburg, 1971, 1973, 1975).

1.4. Abnormal Vision:

The psychophysical methods discussed above have been applied in the study of normal vision and for the analysis of patients with abnormal vision. The results obtained from persons with abnormal vision can also contribute to the understanding of the visual processing and the underlying pathways. Defects in the central mechanism of vision, the striate or prestriate cortex, may cause various levels of visual disturbances, which can be as severe as blindness or as slight as dyslexia. In the next section I will discuss some forms of visual disturbances.

1.4.1. Visual Agnosia:

Some forms of lesions in the cortex may give rise to different degrees of loss of visual recognition. There are different types of visual recognition defects that can occur in isolation or in combination with others. Some of these types are: prosopagnosia (Bodamer, 1947; Damasio et al., 1982) which is the inability to recognize faces, topographical agnosia (Benton, 1980; de Renzi, 1988) which is the inability to find directions, alexia which is the inability to read and simultanagnosia (Wolpert, 1924) which is the inability to name pairs of things, and visual form agnosia, the inability to recognise objects (Wapner et al., 1978; Humphreys and Riddoch, 1984).

Several cases were reported of subjects with various types of visual form agnosia. One of these cases was of a subject who complained, following a stroke, of severe problems in visual perception, in that he failed to recognize common objects and faces by sight, and he also suffered loss of colour vision and impaired reading, with word recognition reduced to operating at single letter or at most diagram level (Humphreys and Riddoch, 1984, 1987). CT scans revealed extensive neuronal degeneration in the prestriate cortex. Measurements on this subject have shown that his responses to pattern recognition tests are abnormally long for all discrimination measurements, with the exception of orientation discrimination for single lines (Bromley et al., 1986; Alkhateeb et al., 1989) (Fig 1-23). These findings provided evidence of the importance of parallel processing and led to the design of experiments by Javadnia and Ruddock (1988a&b) which in turn led to the presented study.

1.4.2. Dyslexia:

Another kind of visual disturbance is the inability to read or spell words accurately despite conventional instructions, adequate intelligence and sociocultural opportunity. It is a specific kind of congnitive functional disorder which is not caused by any known lesions. It was found that the dyslexics failed to make use of sequential redundancy in the identifications of letters, and made many types of confusion error compared to controls (Newton et al., 1979). This problem could be due to unstable eye movements during reading or could be due to a general tendency for left hemisphere functions to be carried out less effectively by dyslexics than normals (Ellis, 1984), since most language processes are the responsibility of the left hemisphere (Springer and Deutsch, 1981), and since the acquired dyslexias are known to arise from left hemisphere injuries (Newcombe and Marshall, 1981).

Pattern discrimination measurements for a single subject with dyslexic problems showed that responses for discrimination of elements such as triangles are markedly different from normal subjects (Fig 1-24) (Ike and Ruddock, 1987), while for elements constructed of dots or lines responses were similar to normal subjects. In other unpublished work it has been shown that dyslexic subjects are less able than normal subjects to perform parallel processing with tests of the kind used by Javadnia and Ruddock (1988a).

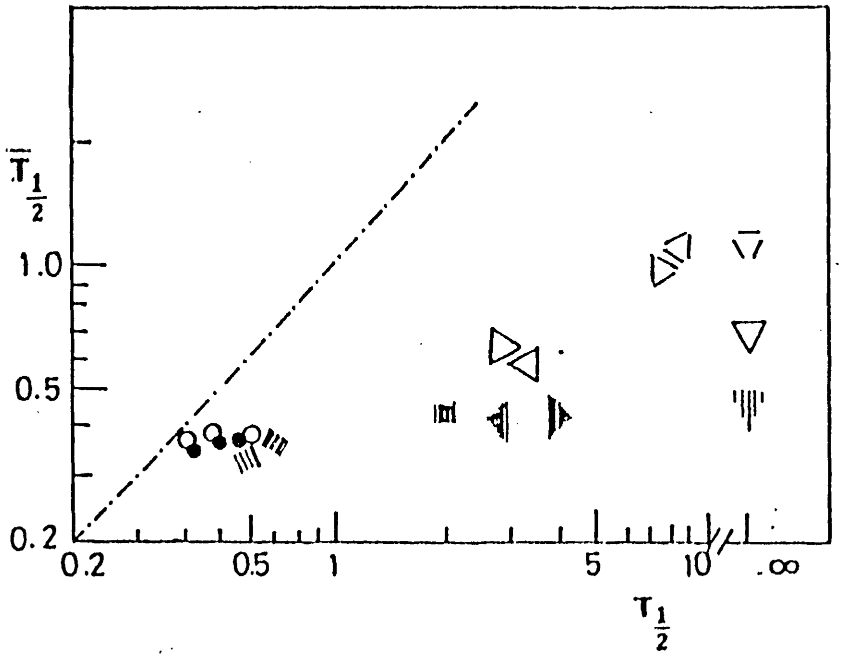


FIG. 1-23. The half time required for detection of targets, oriented as indicated in the Figure. $\bar{T}_{\frac{1}{2}}$, average values for normal subjects, $T_{\frac{1}{2}}$ for HJA, an agnosic subject. In each case, the reference field consisted of 40 elements, oriented upright (e.g. △). The circles correspond to data for continuous lines (o), or five coliner spots (•) and data for three different line target orientation give the only near-normal values for HJA. (From Bromley et al., 1986).

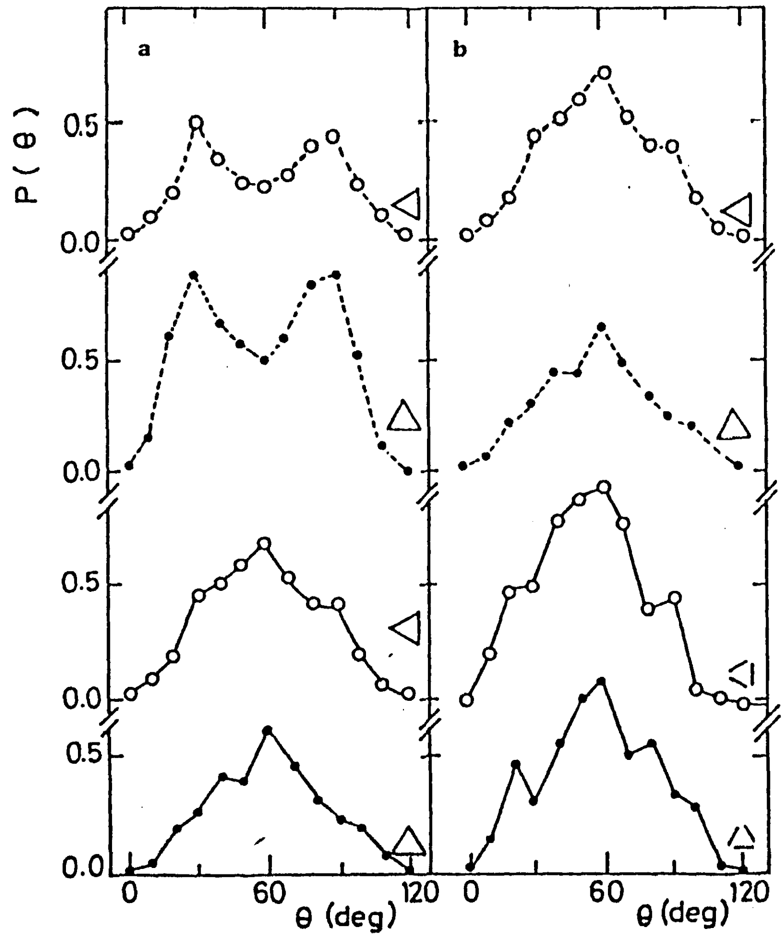


FIG. 1-24. Probability of target detection, P(θ), plotted against the rotation angle of the target, θ. There were 60 background elements; and measurements were made with different orientation of the reference elements as indicated on the diagram. (a) Full lines for dyslexic subject, A.P., broken lines, data for normal subject taken from Ike et al., (1984). (b) For elements ⧋ and ⊲| , as marked, and comparison data for △ ◁ , (broken line), taken from (a). Subject A.P. (From Ike and Ruddock, 1987).

1.4.3. <u>Colour Vision Defects:</u>

Defective colour vision involves loss of ability to discriminate between stimuli of different spectral compositions, and such conditions can arise from either congenital or acquired factors.

Congenital colour vision defects are divided into three general catagories depending on the colour matching characteristics associated with the defect. In the most severe cases subjects can match all spectral stimuli against each other merely by adjusting the relative brightness. This corresponds to a complete loss of colour discrimination and is known as monochromacy or achromacy. In the most common form (incidence of $1:10^4$) subjects lack functional cones, and the vision is characteristic of rod, or night vision in normal subjects. Dichromacy corresponds to the conditions when subjects require only two matching stimuli to match all spectral stimuli. Red-green dichromacy is a sex-linked condition, involving about 2% of the male population: 1% of these are protonopes, who lack the red-sensitive photoreceptors and the other 1% are deuteranopes who lack the green-sensitive photoreceptors. In the female population, these defects occur with frequency P^2 where P is the frequency in the male population. These two defects involve loss of discrimination between reds and greens. Tritanopia, the absence of the blue mechanism, is a rare (estimated 1 in 10^4 to 1 in $5x10^4$) and is not sex linked. It involves loss of discrimination between blues and greens.

Anamolous trichromats require three variables to make all possible colour matches, but the matches are different from those of normals. If they require more red than normal in the Rayleigh match between a yellow and a mixture of red and green, they are called protoanomalous, and if they require more green they are called deuteranomalous; the former have an incidence of about 1% in the male population and the latter 5%. Tritanomaly, which involves lack of discrimination between blue and green spectral stimuli, is very rare and its characteristics are not well studied.

A new class of central colour vision deficiency was found (Bender and Ruddock, 1974; Hendricks et al., 1981; Holliday et al., 1982; Alkhateeb et al., 1987), where a subject was shown to have normal achromatic vision but exhibits grossly abnormal responses to coloured and particularly red stimuli. He has a strong spreading spatial inhibition for red objects (Fig 1-25), which also occurs to a lesser extent with other colours, except yellow. The inhibitory region increases in size as the object size increases and the effect increases as the colour saturation increases. His visual responses to white light are normal, and stereoscopic depth perception is normal even for red green random dot stereograms. The visual defect of this subject seems to be central in the visual pathways, and probably arises in the homologous of area V4 of the monkey prestriate cortex. A short paper on this subject, showing unusual mapping of the visual field, measured in terms of spreading inhibition, is included with this thesis.

1.5. Objectives of the Present Research:

In previous researches based on the pattern discrimination methods, the limits for parallel processing of orientation and magnification discriminations were found (Ike et al., 1987; Javadnia and Ruddock, 1988a) for simple reference fields,

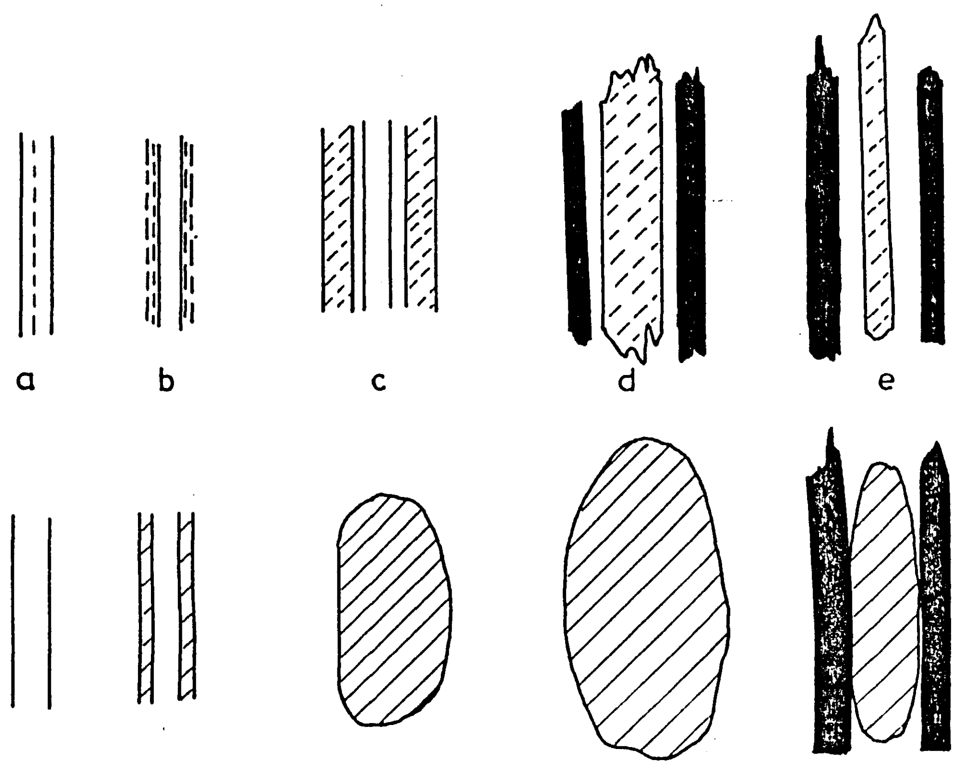


FIG. 1_25. The upper row shows a set of five stimulus patterns (a to e), consisting of black bars, denoted by the fully shaded areas and red bars, denoted by the broken lines or hatched areas. The lower row shows M.'s hand-drawn illustrations of the appearance of these patterns; the hatched areas denote regions which appeared 'silvery-grey' and the fully shaded areas appeared black, with well defined edges. (From Hendrick, et al., 1981).

consisting of a single class of element. To investigate the discrimination of magnification and orientation of simple geometric patterns a step further, similar studies were performed with more complex reference fields. Various field configurations were constructed for each aspect of the problems to be investigated. In the initial experiments, the reference field for orientation discrimination consisted of equal numbers of two classes of elements, which differed from each other in orientation. Corresponding experiments for magnification discrimination were performed with two classes of reference elements which differed in magnification, and the results of this study are presented in Chapter Three.

This method of investigating spectral discriminations was extended by introducing a second parametric difference between the two classes of reference element. For example in experiments dealing with orientation discrimination the two classes of reference elements were also distinguished by colour, by luminance or by contrast polarity, and in this way it was possible to investigate the sensitivity of the orientation selective mechanisms to these parameters, and similar experiments were performed on magnification discrimination. Data for both studies are presented in Chapter Four.

The same principle was applied to examine the interaction between orientation and magnification in such discriminations. In this case, one set of reference elements differed from the other in both magnification and orientation, and discrimination of both parameters was examined (see Chapter Five).

Two further sets of experiments were performed, with a single class of reference element, as studied previously by Ike et al., (1987) and by Javadnia and Ruddock (1988a,b). Two parameters were examined in these experiments: firstly, the discrimination of differences in luminance between the target and the reference element (see Chapter Six) and secondly, the discrimination of elements made more complex by the addition of a circle to the normal geometrical element. Ike et al., (1987) found that enclosing simple geometrical elements in a circle made discrimination of relative orientation more difficult, and the aim of this study was to determine whether it was enclosure of the geometric element or simply the addition of the circle which was the critical factor (Chapter Seven).

CHAPTER TWO

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Chapter Two
Experiments and Method

2.1. Introduction:

Previous experiments were performed (Javadnia and Ruddock, 1988a,b) to clarify some aspects of spatial discrimination. It was found that a target embedded within a number of identical reference elements, which differ from the target either in magnification or orientation, can be distinguished easily, and that discrimination performance does not depend on the number of reference elements. This was true for targets that have an orientation difference greater than 5 degrees, or for targets of magnification difference of more than 10% to 20% in the linear dimension relative to the reference elements.

My work takes a step further in this approach by examining discrimination for reference fields which are not composed of identical elements. The reference field consisted of two elements, which could be mixed in equal numbers to obtain the desired number of reference elements in the field, see Fig 2-1.

The experiments were performed with two separate pieces of equipment, each programmed to produce the reference elements and a target element on a monitor, which was viewed by the observer.

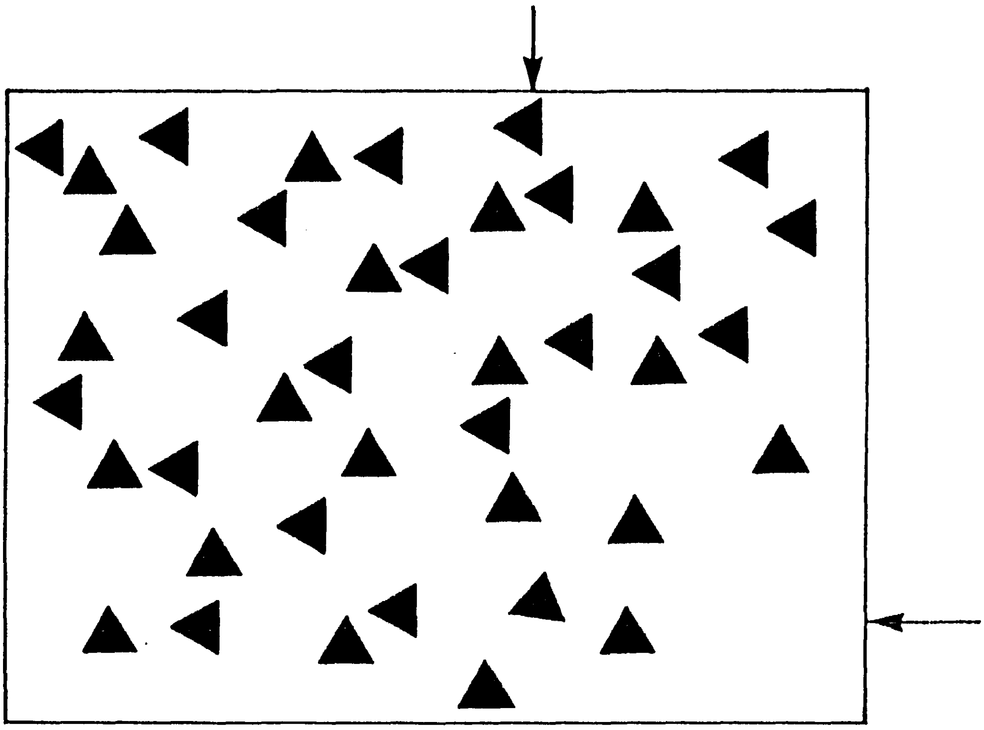

FIG. 2-1. A typical display showing a reference field of mixed orientation with two classes of element of 0° and 30° orientation. The target location is denoted by the arrows.

2.2. Equipment:

2.2.1. The Sharp System with Pluto Board:

The equipment used in this experiment consists of a colour monitor controlled by a microcomputer (Sharp MZ-80B) via a colour graphic board (IO Research, Pluto Board) . The microcomputer has its own integral monochrome monitor used by the experimenter and attached to it are two floppy disc drives on which programs and data are stored, a printer (Sharp MZ-80) used to produce copies of the experimental data, and a reply box. The reply box, which is connected to the computer via a universal interface card (MZ-80102) consists of a metal box with two reply buttons for use during the experiments, a joystick, a push button switch and a toggle switch (the last 3 items are used in creating new experiments). The apparatus was used to perform experiments for the measurement of visual discrimination between simple patterns. A program called "Multiback", written in Z-80 assembly language for speed of execution, was used to carry out these pattern discrimination experiments. This program enables us to produce a multiple of up to four different elements in the reference field, with one of three other elements acting as the target. This target is chosen randomly and embedded in the visual field. The various reference and target elements are distributed randomly and are non-overlapping. In 25% of the presentations, a target element identical to one of the reference elements was used as a null target. The required elements are drawn using part of the program called "Learn". This part of the program was written specifically to allow the experimenter to draw and amend targets on the screen using the joystick and buttons on the reply box. New targets could be saved onto a floppy disc for use in later experiments. Eight different colours can be used for drawing the targets and each of these colours could have any value between 0 and 255 for each of the red, green and blue guns, giving a possibility of 16.7 million different hues.

2.2.2. The IBM PC System:

This system consisted of an IBM PC-AT Enhanced personal computer with a hard disc and two floppy discs attached to it. The hard disc has a capacity of 20 Mega Bytes and of the two floppy discs, one has 1.2 Mega bytes capacity and the other 512K bytes. Connected to the computer is a high resolution enhanced colour display monitor (IBM Quadram), an Epson FX80 Printer and a joystick. An enhanced Graphics Adaptor (STB EGA) card was added to the IBM computer to improve the graphic capability of the system. A Math Co-processor 80287 card was also added to the computer to improve the process of the program.

The programs which were used are saved on the hard disc and were written in quick basic language then compiled. Two programs were written; one of them is "Rasm" which was used to draw the patterns needed in the experiments by the use of the key board. These patterns are saved under a sequence name for later retrieval to be used during the experiments, each sequence file consisting of five patterns. The other program is "Generate"; this program has several functions: first, to choose the sequence file needed during the experiment; second, to choose which two patterns out of the five drawn would be used as the reference elements leaving the remaining three to be used as targets, third to specify the number of elements per reference per presentation, introducing the targets randomly, and fourth to measure the time lapse between the appearance of the patterns on the monitor and the push of the reply button on the joystick. The joystick has two reply buttons, one stands for "Yes" reply and the other for "No" reply. The only limit in this system compared to that for the Sharp system is that the EGA card has capacity of only 16 colours compared to the 16.7 million hues available with the Pluto.

2.3. Method:

Using the two systems the different patterns drawn consisted mainly of lines, triangles and squares of various orientations, magnifications and colour. These shapes or patterns were saved on a disc under a sequence name. A file could be made where these patterns are requested to appear on the monitor in a certain number of duplicates, N, and the two reference patterns or elements could be presented in multiples of one of each reference element to twenty of each reference element. In each experimental run, there were 100 presentations, 25 of which consisted of only the reference elements plus one extra, chosen from the reference element. The remaining 75 presentations consisted of 25 of each of the three targets, chosen randomly in each of the 100 presentations.

The observer was requested to push one of two buttons after each presentation in order to respond - "Yes, there is a target present on the monitor, the visual field," or "No, there is no target present". The 'No' responses provide a measure of the observer's accuracy. The time lapse for each reply is considered as the response time for this target and is recorded and saved under a data file name. At the end of each set of measurements, the computer displays both the distribution of the response times and the cumulative number of responses as a function of time. The reference elements for each experiment and their number, N, were varied, and the target was one of three different elements. The position of the target and reference elements and the type of target element are designated randomly by the computer for each presentation. Successive presentations were made immediately following the observer's response, and at the end of 100 presentations, the results could be displayed as a time distribution or cumulative response of the probability of target detection as a function of time. Three cumulative response curves are displayed one for each target type and a fourth curve displays the total number of yes replies to the null target presentation. A measure of the observer's response was provided by $T_{\frac{1}{2}}$, the time required to obtain 50% probability of detection of the target. This is illustrated in Fig 2-2. As explained, the number of "false positives" for the "null targets" provided one measure of the observer's accuracy, but a further measure is provided by the number of failures in detection of the true targets.During the experiment the observer was seated 1.8m away from the monitor screen which then subtended 8.5 degree x 6.3 degree at the eye. The room was darkened and the observer looked straight ahead at the display monitor. The experimenter could see the running total of the number of presentations for each target and the number of these detected by the observer in the microcomputer's integral monitor, and the number of targets that the observer failed to detect was noted at the end of each experiment.

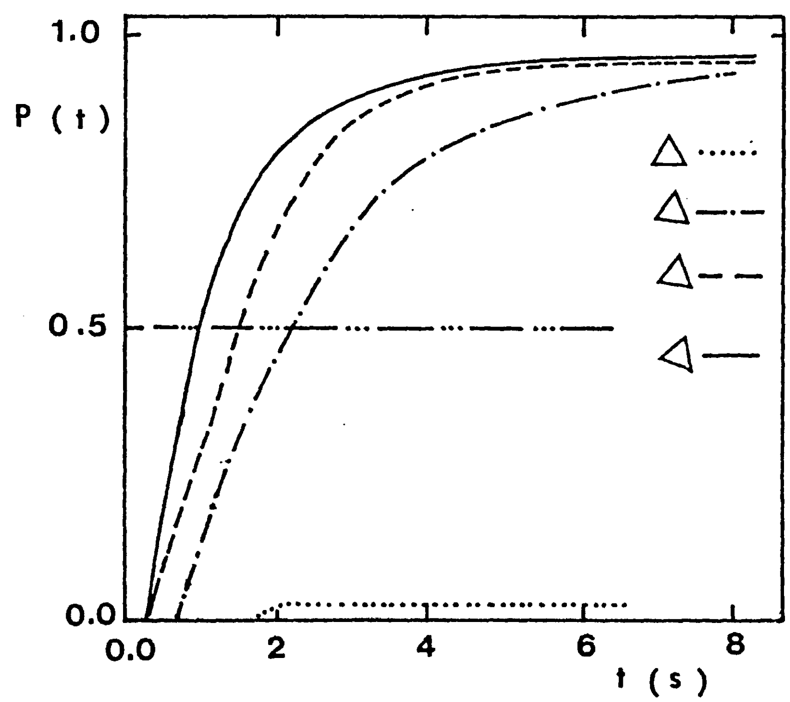

FIG. 2 - 2. The probability of detecting the different targets, P(t), plotted against the time of presentation, t. The line, —··—···, corresponds to 50% probability of detection and determines the half time, $T_{1/2}$, for each target. The data ..... corresponds to the null target △, which is identical to the reference elements.

2.4. Calibration of Screen Gun Colour and Luminance:

In order to calibrate the screen of the colour monitor, a digital radiometer/photometer (Macam, Model PR3010) with a sensitive detector area of 1cm diameter was placed 30cm from the screen. It was used to measure the luminance of the center of the screen as a function of the gun value for each of the three electron guns. Each gun could have any integral value between 0 and 255 inclusive and on its own gives a red, green or blue coloured screen the luminance of which increases with the gun number from 0 to 255. The screen was calibrated by:

1. Taking a reading on the photometer starting with one of the three guns at the maximum value of 255.
2. A calibrated 0.5 neutral density filter (NDF) was placed in front of the detector and a second reading was obtained. Using the above NDF allowed us to reduce the log luminance in steps of 0.05.
3. The NDF was removed and the gun value was decreased until the same reading on the photometer as in 2 was obtained.

Fig 2-3 shows a graph of screen relative luminance versus gun value for the red, green and blue guns. All three guns seem to be following the same range of relative luminance, with the red one tailing off at the higher gun values.

2.5. Half Time ($T_{\frac{1}{2}}$) Measurements:

The response time, $T_{\frac{1}{2}}$, is the time lapse between the presentation of the pattern on the screen and the subject's pushing the positive reply button, denoting

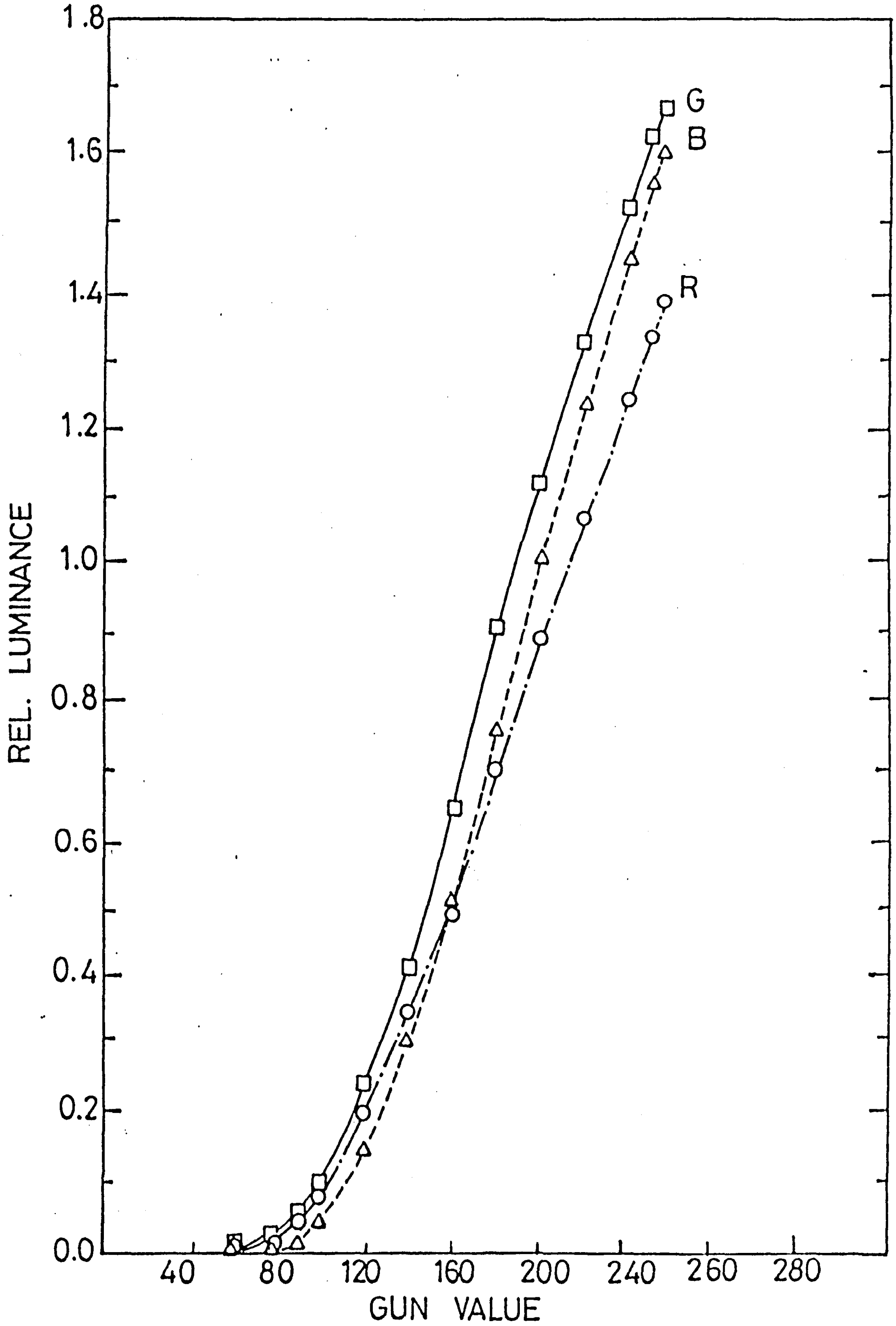

FIG. 2-3. Screen relative luminance versus gun value for the red, green and blue guns of the monitor.

target seen. The relation between the time and the number of targets detected within this time is displayed by the computer. The graph of the time against the probability of finding the target is drawn, see Fig 2-2. The time required to distinguish a target on 50% of presentations is called the half-time, $T_{\frac{1}{2}}$, for that target.

In each experimental session the number of reference elements is fixed and separate sessions were performed for various numbers of reference elements. The half-time for each experiment was calculated using another program called "half", which calculates the time of which 50% of the targets were detected.

The relation between the number of reference elements and the half time for detecting each target was evaluated. The half time is the basis of our evaluation of the visual processing mechanism, with it we can distinguish between parallel processing and serial processing by examining the relationship between $T_{\frac{1}{2}}$ and the number of reference elements.

2.6. Plan of Experiments:

The experimental systems described previously were used to investigate a variety of discrimination tasks, which can be summarized as follows:

1. The discrimination of target orientation from a reference field consisting of a mixture of two classes of elements with different orientations.
2. The discrimination of target magnification in a reference field consisting of a mixture of two classes of elements with different magnifications.

3. The discrimination of target spatial parameters from reference fields composed of two classes of elements distinguished by colour, as well as by orientation or magnification.
4. The discrimination of target spatial parameters from reference fields composed of two classes of elements distinguished by luminance as well as by orientation or magnification.
5. The discrimination of target spatial parameters from reference fields composed of two classes of elements distinguished by contrast polarity, as well as by orientation and magnification.
6. The discrimination of target spatial parameters from reference fields composed of two classes of elements distinguished both by orientation and magnification.
7. The discrimination of target spatial parameters from reference fields, in which the elements are more complex than the simple elements used in 1 to 6.

Each experiment will be described separately and the elements used will also be illustrated.

2.6.1. Discrimination of Target Orientation with a Reference Field with Mixed Orientation:

As in most other experiments, the elements were in the form of lines, equilateral triangles or squares all of which were green, made up of green with relative luminance, of 0.54 value plus blue with 0.17 relative luminance on a black background screen (zero gun colour for all three colours Green, Blue and Red). The two dimensional figures were solid green. The various combinations of target and reference elements are illustrated in Fig 2-4, and in these experiments, the

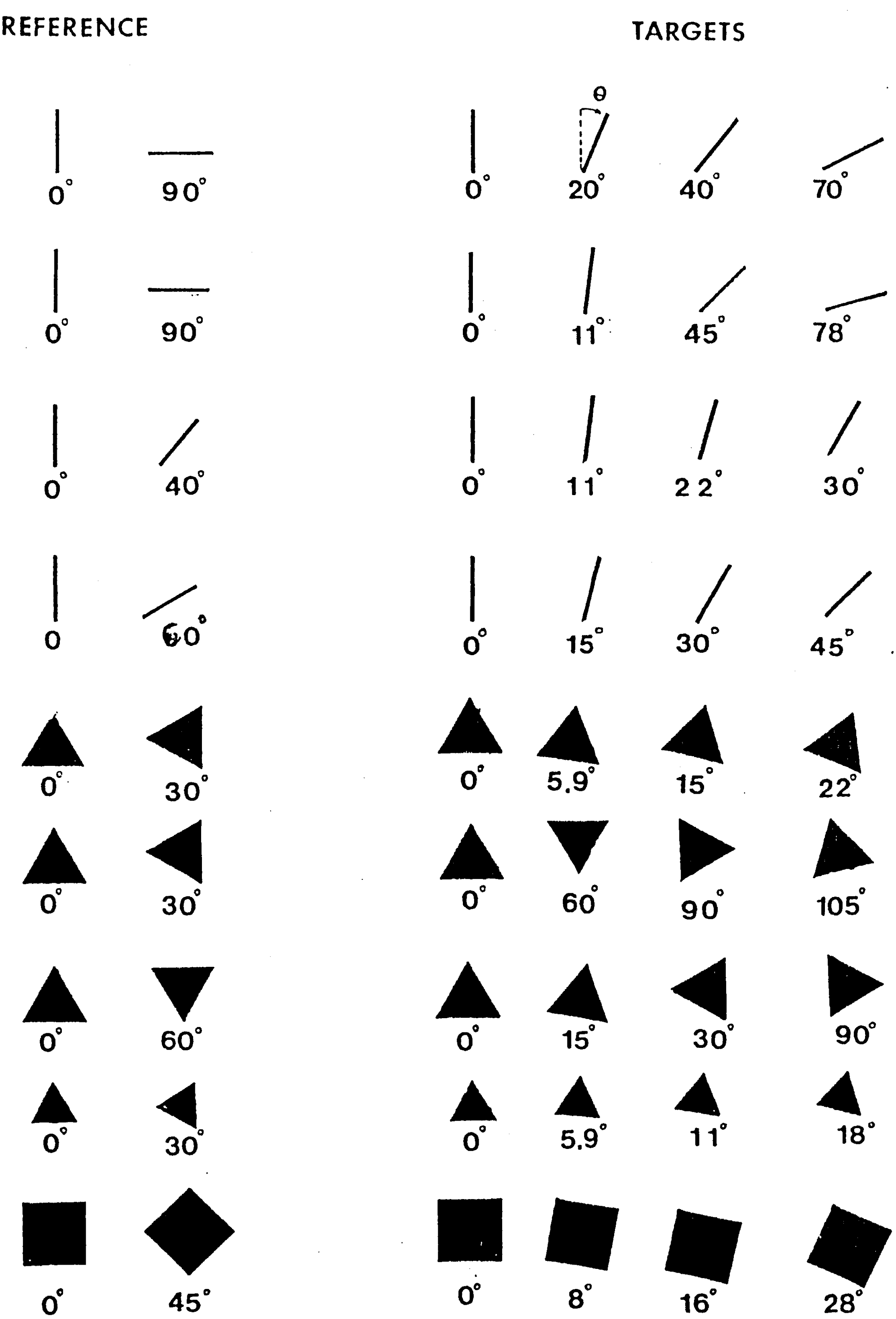

FIG. 2_4 · Various combinations of target and reference elements of mixed orientations. The data obtained with these stimuli are presented in figures 3-2 to 3-17.

targets were of side length 0.50 degree for lines, 0.45 degree for the side of large equilateral triangles, 0.23 degree for small equilateral triangles and 0.36 degree for the side of the squares. The measurements were performed with 1, 2, 3, 5, 10 and 20 of each reference element in the reference field, and comparison measurements were carried out with from 2 to 40 of each reference element presented separately in the reference field. An example of the display of 20 each of the reference element and a target is seen in Fig 2-1. The results of these experiments are presented in Chapter 3.

2.6.2. Discrimination Of Target Magnification With A Reference Field With Mixed Magnification:

In these experiments also, the elements were in the form of lines, equilateral triangles or squares, all of which were green in colour (Green relative luminance 0.54 + Blue relative luminance 0.17), the squares and triangles being solid figures, presented on a black background screen (all gun colours, green, red and blue at zero). The various combinations of target and reference elements are illustrated in Fig 2-5 and in these experiments the sizes of the reference elements, which are considered as having 100% magnification, are as follows:

Line	=	0.50 deg.
Side of Equilateral Triangle	=	0.45 deg.
Side of Square	=	0.45 deg.

The measurements were performed with 1,2,3,5,10 and 20 of each reference element in the reference field. In comparison, measurements were carried out with 2 to 40

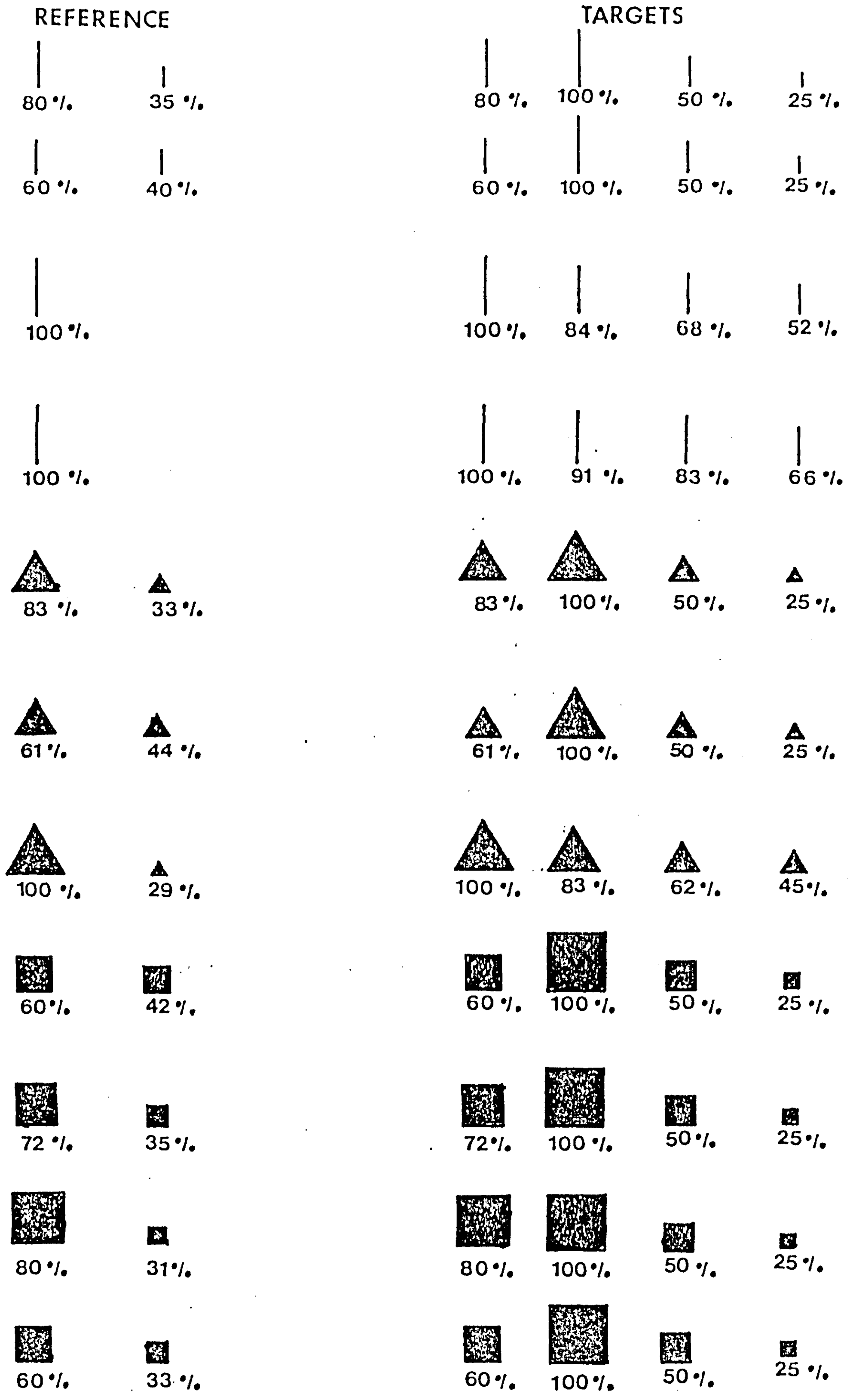

FIG. 2-5. Various combinations of targets and reference elements of mixed magnification. The data obtained with these stimuli are presented in Figures 3-19 to 3-32.

of each single reference element in the reference field. The results of these experiments are presented in Chapter 3.

2.6.3. The Discrimination of Target Spatial Parameters with Reference Fields composed of Two Colours:

In this type of experiment, the reference field consisted of two classes of elements distinguished by colour, as well as by orientation or magnification. The target colour was the same as that of one of reference classes. Orientation measurements were made with two classes of reference element which differed in relative orientation, as well as colour, and magnification measurements with two classes which differed in relative magnification and colour, Fig 2-6.

The colours were chosen on the basis that they are matched approximately in luminance. In most of the experiments the targets were viewed against a black background screen (green, red and blue gun values at zero) and others were against yellow or white background screen. In most experiments the reference field consisted of red and green elements with relative luminance set at 1.0. The chromaticity co-ordinates of the various colours used in the experiments are plotted in the C.I.E. 2 deg chromaticity chart (Fig 2-7). In order to assess the importance of matching the relative luminances of the red and green elements, measurements were also made in which the luminance of one colour component was constant and the other set at a series of different values.

Some experiments were carried out with reference fields consisting of blue and yellow elements. These two colours were set to approximately the same luminance,

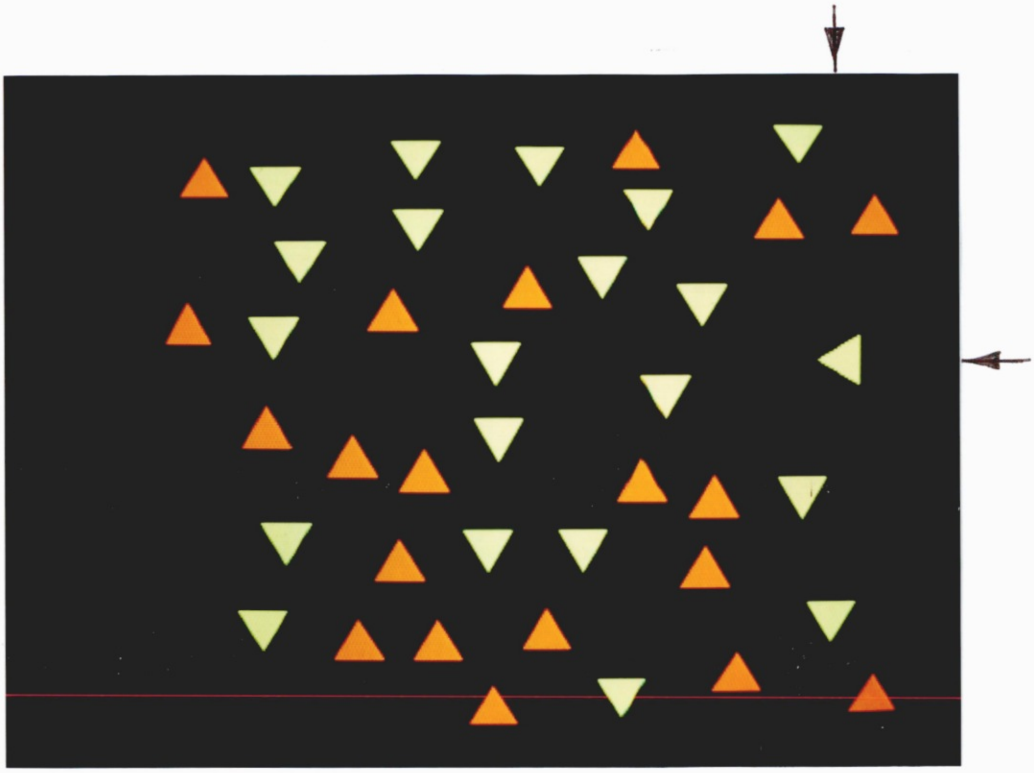

FIG. 2-6. A typical display showing a reference field for colour and orientation discrimination measurements. The target is denoted by the arrows.

with the blue at relative luminance 1.0 and the yellow composed of a mixture of red, (relative luminance 0.88) and green, (relative luminance 0.91).

The background screen colour was in some cases black (gun values for red, green and blue at zero) during the experiments but in other cases the background was set at an equiluminance colour, intermediate between that of the two reference colours. Thus for the red and green reference elements, the background was yellow, and for the yellow and blue reference elements, the background was white. Again these colours are marked in the chromaticity chart of Fig 2-7. Table 2-1 shows the various combination of colours and relative luminance used in these experiments.

The sizes of the elements were the same as those used in section 2.6.1 and 2.6.2. The measurements were performed with 1, 2, 3, 5, 10 and 20 of each element in the reference field. The results of these experiments are presented in Chapter 4.

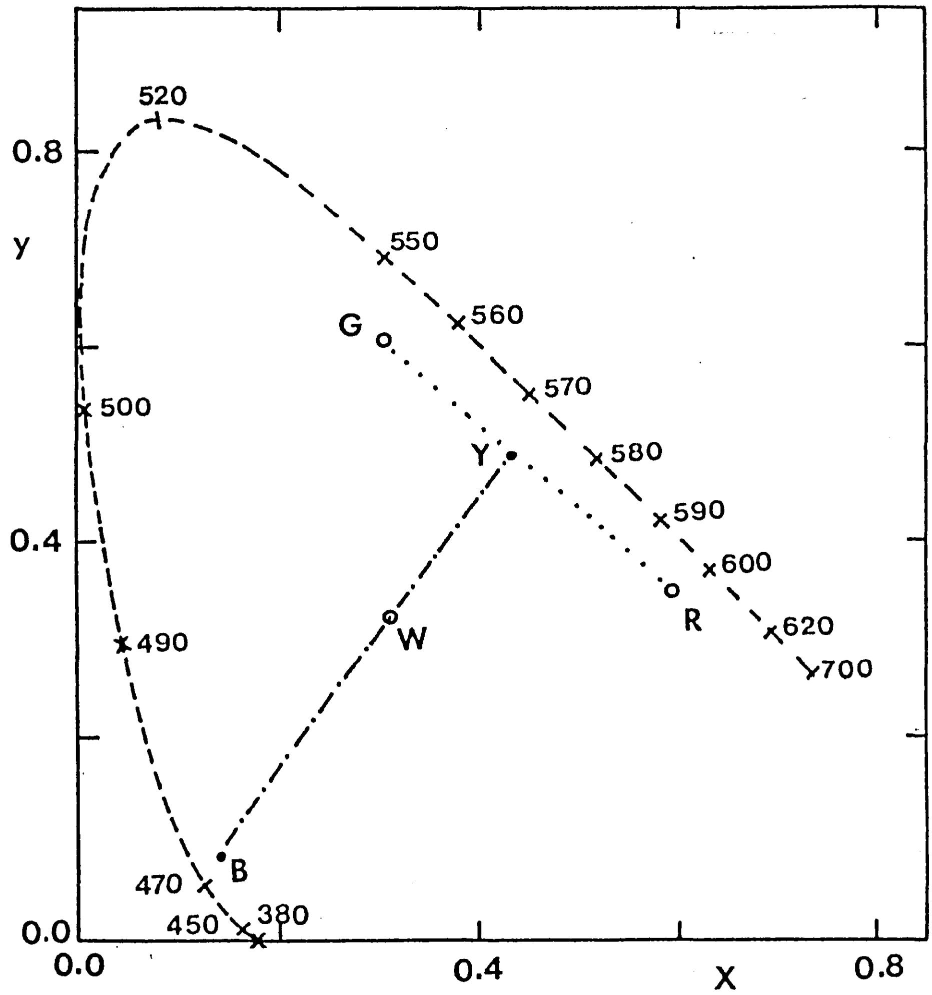

FIG. 2-7. C.I.E. 2° x-y chromaticity chart, showing the chromaticity co-ordinates of the stimuli referenced in the text as red (R), green (G), yellow (Y), blue (B) and white (W). The different lines connect pairs of stimuli used together to form colour contrast stimuli. The chromaticity co-ordinates of the spectral stimuli are denoted by the wavelength nm.

Table 2-1. The various combinations of colours and relative luminance used in the discrimination of targets from reference fields composed of two colours.

Reference 1	Reference 2	Target	Background
Red x=0.593, y=0.348 Rel.lum.=1.0	Green x=0.300,y=0.602 Rel.lum.=0.76,0.96, 1.0,1.067,1.225	Red x=0.593 y=0.348 Rel.lum.=1.0	Black
Green x=0.300, y=0.602 Rel.lum.=1.0	Red x=0.593,y=0.348 Rel.lum.=0.504,0.756, 0.777,0.903,0.95,1.0, 1.037,1.083,1.14, 1.24	Green x=0.300, y=0.602 Rel.lum.=1.0	Black
Yellow x=0.433, y=0.490 Rel.lum.=1.0	Blue x=0.176 y=0.100 Rel.lum.=1.0	Yellow x=0.433, y=0.490 Rel.lum.=1.0	Black
Green x=0.300, y=0.602 Rel.lum.=1.0	Red x=0.593 y=0.348 Rel.lum.=1.0	Green x=0.300, y=0.602 Rel.lum.=1.0	Yellow x=0.433, y=0.490 Rel.lum.=1.0
Red x=0.593, y=0.348 Rel.lum.=1.0	Green x=0.300, y=0.602 Rel.lum.=1.0	Green x=0.300, y=0.602 Rel.lum.=1.0	Yellow x=0.433, y=0.490 Rel.lum.=1.0
Yellow x=0.433, y=0.490 Rel.lum.=1.0	Blue x=0.176 y=0.100 Rel.lum.=1.0	Yellow x=0.433, y=0.490 Rel.lum.=1.0	White x=0.316 y=0.330

2.6.4 The Discrimination of Target Spatial Parameters with Reference Fields composed of Two Classes of Elements distinguished by Luminance as well as by Orientation and Magnification:

The elements used in these experiments consisted of the equilateral triangles, one of the shapes used in the previous sections. The reference elements and targets were coloured either green or red, and their luminance was varied by controlling the appropriate gun value. In each set of measurements, the luminance of one class of reference element and that of the target was kept constant, whilst that of the other was varied. For example, with a constant red gun luminance of 1.0 for the targets and for one class of reference element, measurements were made with the other class of reference element set at each of series of luminances, as defined in Table (2-2). A similar set of measurements were performed with green reference elements, and in both cases, the background screen was black. The orientation and magnification values of the reference elements and targets were similar to those described in section 2.6.1 and 2.6.2. The measurements of $T_{\frac{1}{2}}$ were performed with 1,2,3,5,10 and 20 of each reference elements in the reference field. The results of these experiments are presented in Chapter 6.

Table (2-2) Various combination of Colour and Relative Luminance used in the Discrimination of Luminance and Orientation

Reference 1 Colour and Relative Luminance	Reference 2 Colour and Relative Luminance	Target Colour and Relative Luminance
Red x=0.593,y=0.348 Rel.lum.=1.0	Red x=0.593,y=0.348 Rel.lum=0.504,0.756, 0.903,0.95,1.0,1.037, 1.083,1.14,1.24	Red x=0.593,y=0.348 Rel.lum.=1.0
Green x=0.300,y=0.602 Rel.lum.=1.0	Green x=0.300,y=0.602 Rel.lum.=0.647,0.90, 0.96,1.0,1.067, 1.187,1.327,1.520	Green x=0.300,y=0.602 Rel.lum.=1.0

2.6.5. <u>The Discrimination of Target Spatial Parameters with Reference Fields composed of Two Classes of Elements distinguished by Contrast Polarity, as well as by Orientation or Magnification:</u>

The elements in the first group of these experiments were in the form of equilateral triangles and squares. In each group of measurements, all stimuli had the same colour but the two classes of reference elements were distinguished from each other by contrast polarity, one class being of positive (brighter elements) and the other negative (darker elements) polarity relative to the background field. The contrast steps of the two subclasses of reference elements were equal in the

Table (2-3): Colour and Relative Luminance of Reference and Target Elements used for Contrast Measurements.

Reference 1	Reference 2	Target	Background
Green x=0.300, y=0.602 Rel.lum.=1.23	Green x=0.300, y=0.602 Rel.lum.=1.23 0.77	Green x=0.300, y=0.602 Rel.lum.=1.23	Green x=0.300, y=0.602 Rel.lum.=1.0
Green Rel.lum.=0.77	Green Rel.lum.=1.23	Green Rel.lum.=1.23	Green Rel.lum.=1.0
Green Rel.lum.=1.23	Green Rel.lum.=1.23, 0.77	Green Rel.lum.=0.77	Green Rel.lum.=1.0
Green Rel.lum.=0.77	Green Rel.lum.=1.23	Green Rel.lum.=0.77	Green Rel.lum.=1.0
Green Rel.lum.=1.43	Green Rel.lum.=1.43, 0.51	Green Rel.lum.=1.43	Green Rel.lum.=1.0
Green Rel.lum.=0.51	Green Rel.lum.=1.43	Green Rel.lum.=1.43	Green Rel.lum.=1.0
Green Rel.lum.=1.43	Green Rel.lum.=1.43, 0.51	Green Rel.lum.=0.51	Green Rel.lum.=1.0
Green Rel.lum.=0.51	Green Rel.lum.=1.43	Green Rel.lum.=0.51	Green Rel.lum.=1.0

positive and negative directions and two pairs of contrasts were used in the experiments (see Table 2-3). In experiments in which the target was distinguished by relative orientation, the two classes of reference elements differed in orientation as well as contrast, and a similar arrangement was used in the measurement of magnification discrimination.

The sizes, magnifications and orientations of the elements used in these experiments were the same as those described in 2.6.1 and 2.6.2. An example of the displays used in these experiments is given in Fig 2-8. The measurements were performed with 1,2,3,5,10 and 20 of each reference element in the reference field. The results of these experiments are presented in Chapter 4.

Experiments on orientation discrimination and contrast were also performed with bars and edges constructed within a square element and the contrast of the bar or the contrast symmetry of the edge were varied. The various combinations of reference elements and targets are illustrated in Fig 2-9.

2.6.6. The Discrimination of Target Spatial Parameters with Reference Fields composed of Two Classes of Elements distinguished both by Orientation and Magnification:

As in most of the other experiments, the elements were in the form of lines, equilateral triangles or squares, all of which were solid green (consisted of green with relative luminance=0.54 mixed with blue of relative luminance=0.17) on a black background screen (zero for all gun colours). The reference elements consisted of a mixture of two classes of elements which differed both in magnification and orientation. The targets had either the

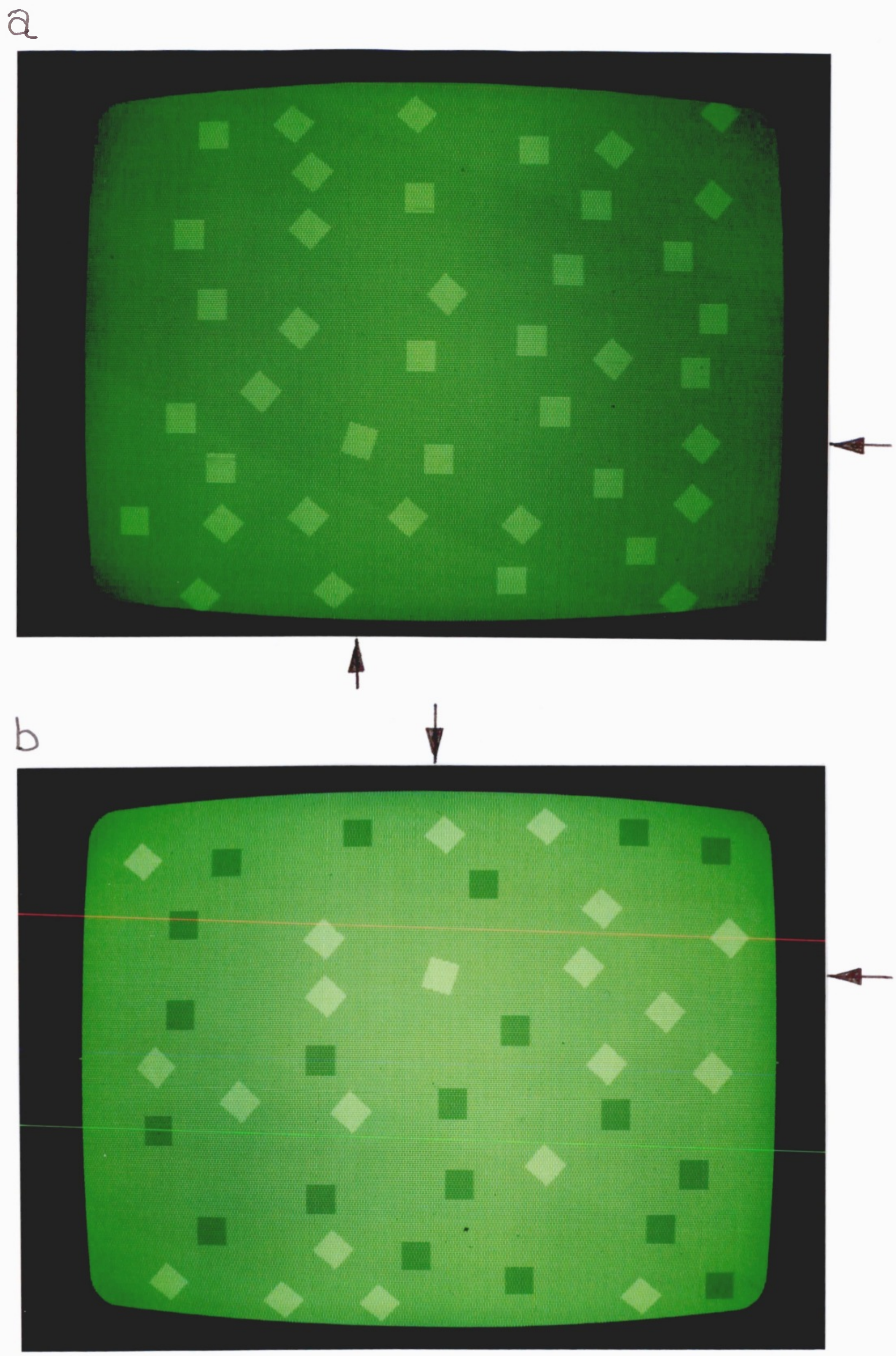

FIG. 2-8. A typical display showing a reference field for contrast and orientation discrimination. The target is denoted by the arrows.
(a) Both reference elements of positive contrast.
(b) Reference elements of positive and negative contrast.

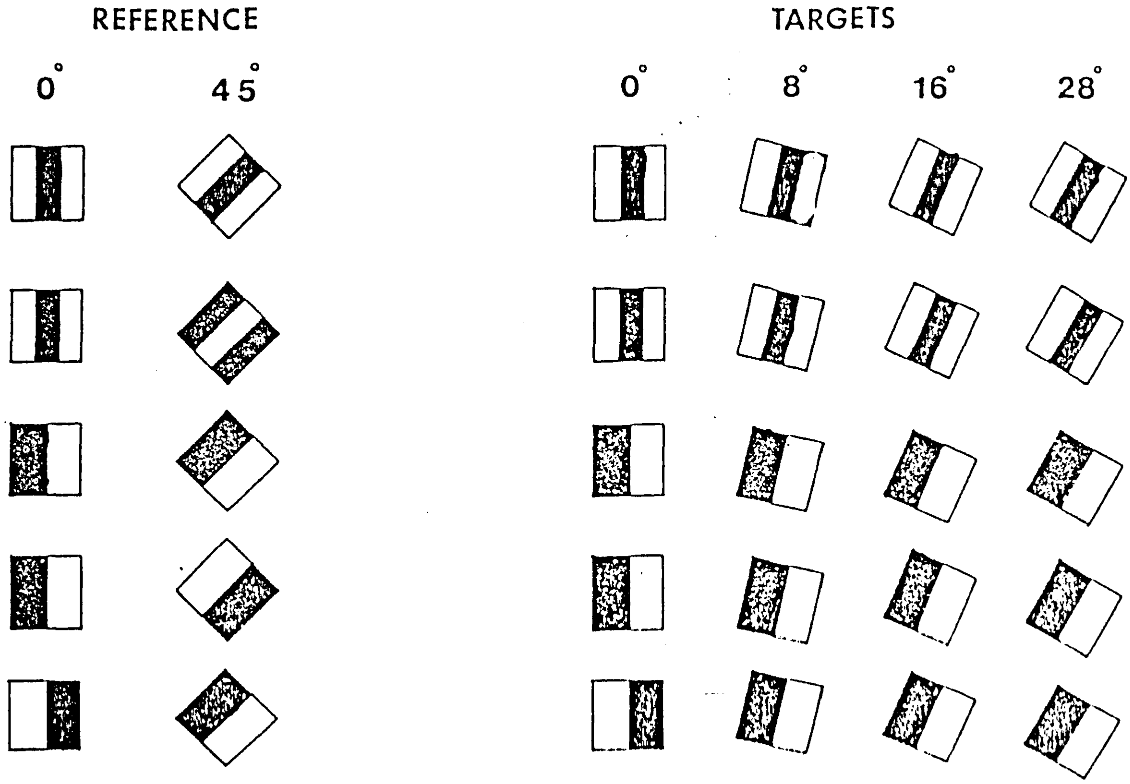

FIG. 2-9. Various combinations of reference elements and targets used for contrast measurements for discrimination of orientation with bars and edges. The relative luminances of the black areas was 1.23 and of the light areas was 0.77 and they were viewed against a background of luminance 1.0

size of one of the classes of reference element and were distinguished from both by orientation, or had the same orientation as one of the classes of the reference element and were distinguished from both classes by size. Fig 2-10 illustrates the various combinations of target and reference elements. The 100% side length corresponded to a visual angle of 0.5 deg. for lines and 0.45 deg. for side of triangles and squares. The measurements were performed with 1, 2, 3, 5, 10 and 20 of each reference element in the reference field. For comparison, measurements were carried out with both of the reference elements separately, from 2 to 40 of each reference element in the reference field. The results of these experiments are presented in Chapter 5.

2.6.7. The Discrimination of Target Spatial Parameters with more Complex Elements:

The reference elements used in some experiments were more complex in structure than the simple elements used in the experiments described in sections 2.6.1 to 2.6.6. They were complicated by the addition of a circular component for the basic pattern, in this case an equilateral triangle, as is illustrated in Fig 2-11. All these elements were green colour (a mixture of green with relative luminance=0.54 and blue of relative luminace=0.17) and were viewed against a black background screen (all colour gun values at zero). The large circles used in the reference element had a diameter of 0.57 deg. with the various shapes emdedded inside it. The small circles within the triangles were 0.25 deg. in size. The measurements were done for 40 identical reference elements in the reference field. The results of these experiments are presented in Chapter 7.

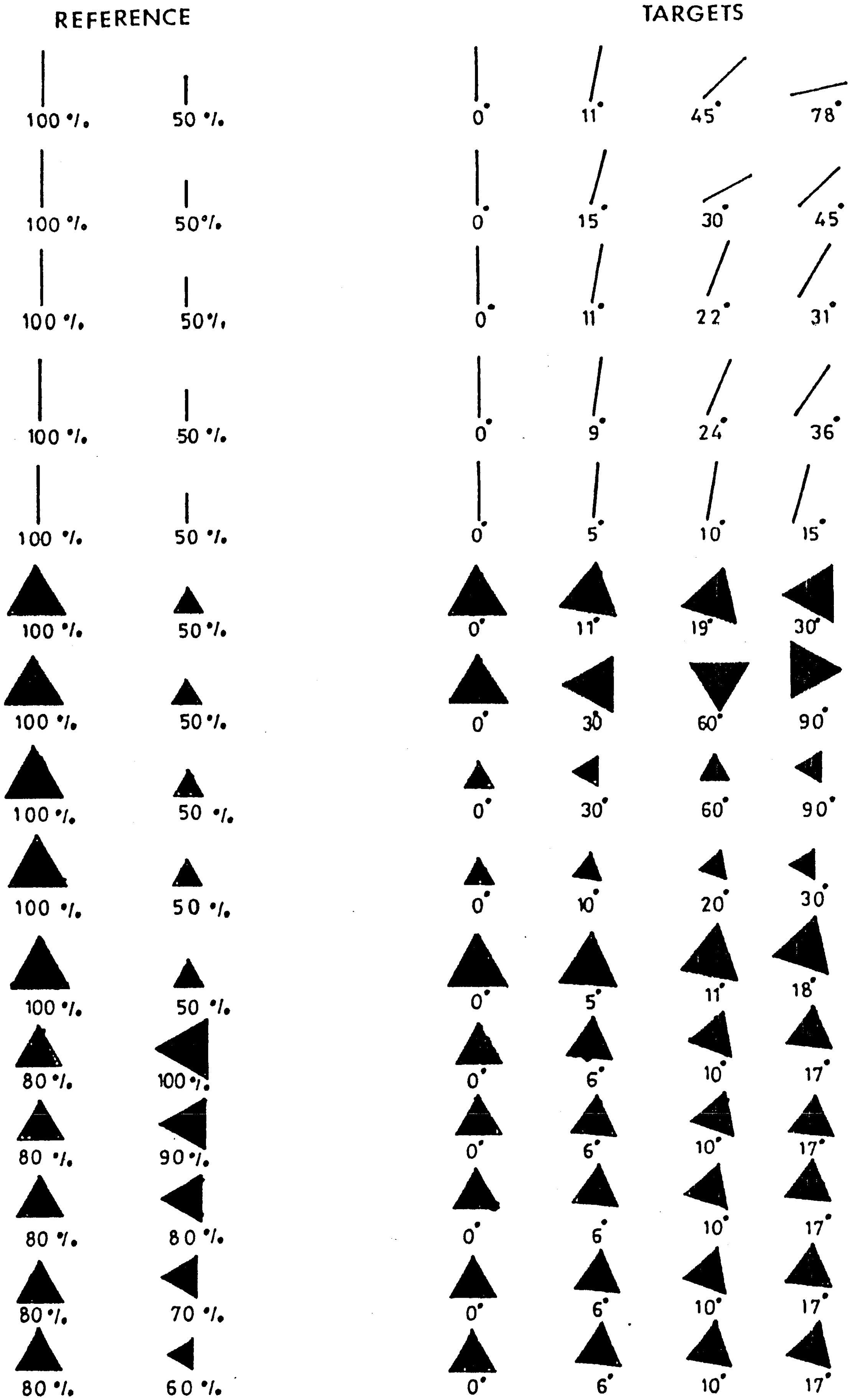
REFERENCE
TARGETS
100 % 50 % 0° 11° 45° 78°
100 % 50% 0° 15° 30° 45°
100 % 50% 0° 11° 22° 31°
100 % 50 % 0° 9° 24° 36°
100 % 50 % 0° 5° 10° 15°
100 % 50 % 0° 11° 19° 30°
100 % 50 % 0° 30 60° 90°
100 % 50 % 0° 30° 60° 90°
100 % 50 % 0° 10° 20° 30°
100 % 50 % 0° 5° 11° 18°
80 % 100 % 0° 6° 10° 17°
80 % 90 % 0° 6° 10° 17°
80 % 80 % 0° 6° 10° 17°
80 % 70 % 0° 6° 10° 17°
80 % 60 % 0° 6° 10° 17°

FIG. 2 – 10a.

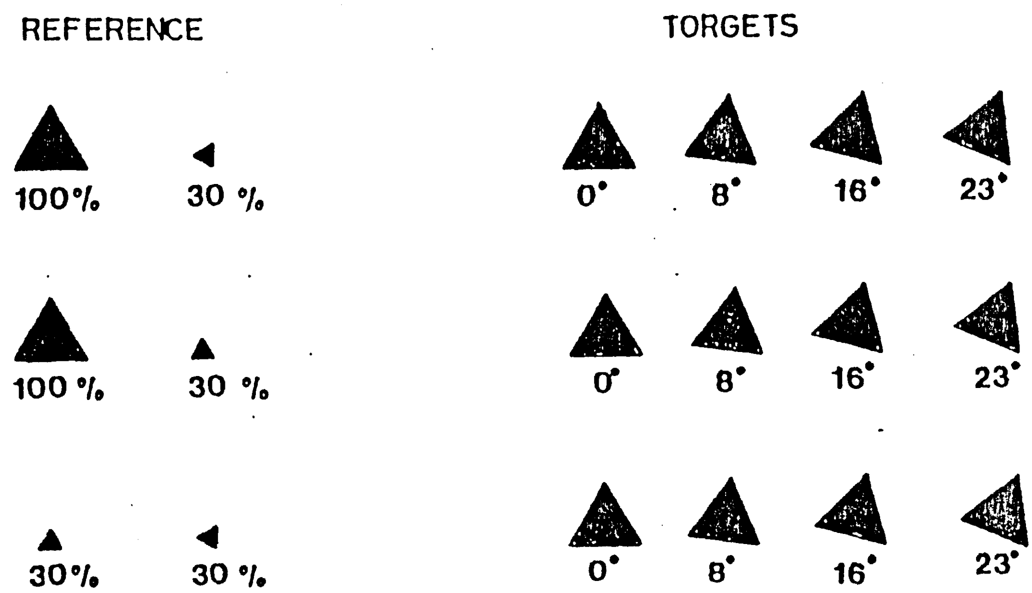

FIG. 2-10a Continued...

Various combinations of reference and target elements used for reference fields of mixed orientation and magnification.

(a) Orientation discrimination for lines and triangles (data in Figures 5-1 to 5-7).

(b) Orientation discrimination for square (data in Figures 5-8 to 5-10).

(c) Magnification dsicrimination (data in Figures 5-11 to 5-17).

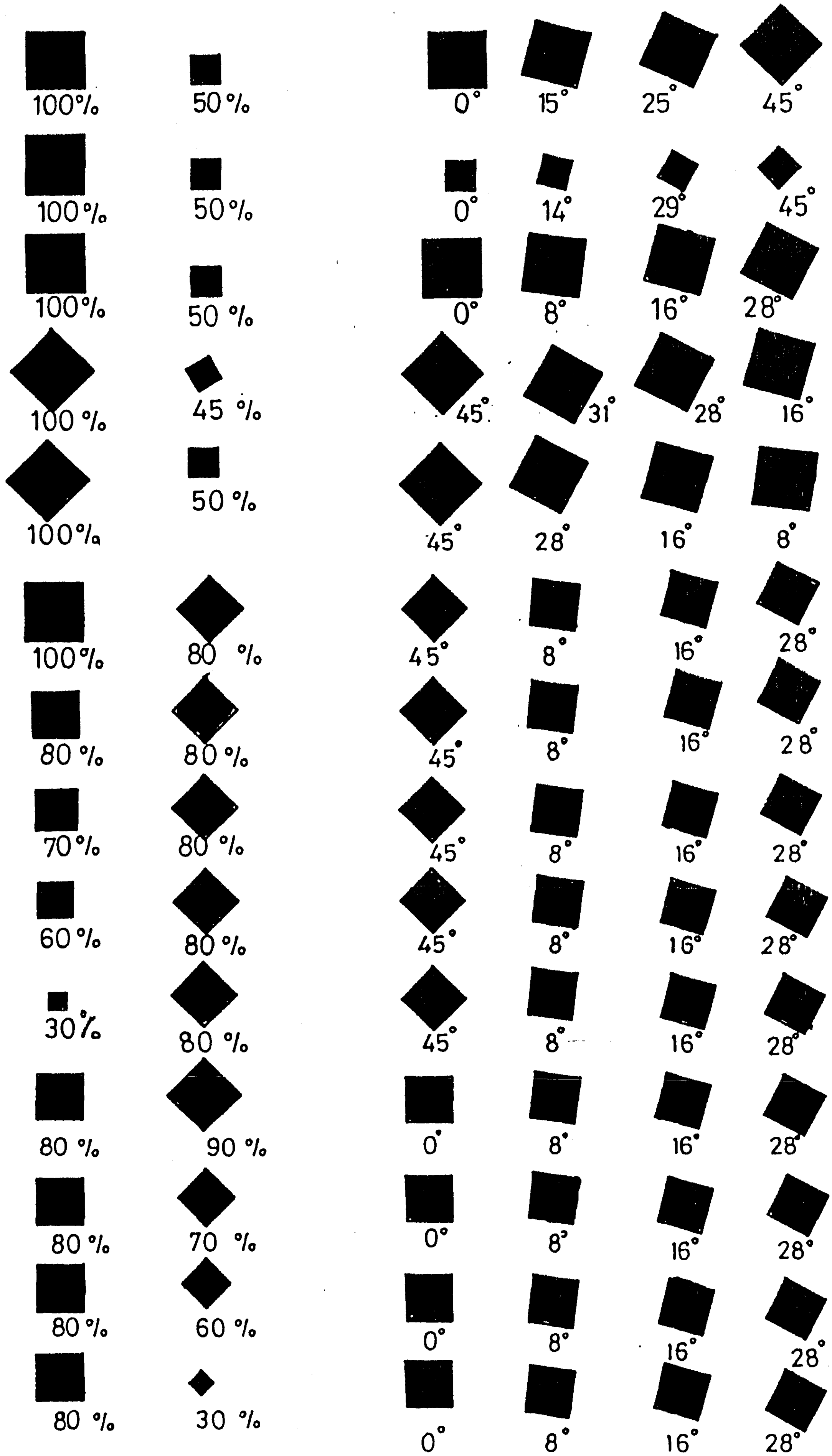
100% 50% 0° 15° 25° 45°
100% 50% 0° 14° 29° 45°
100% 50% 0° 8° 16° 28°
100% 45% 45° 31° 28° 16°
100% 50% 45° 28° 16° 8°
100% 80% 45° 8° 16° 28°
80% 80% 45° 8° 16° 28°
70% 80% 45° 8° 16° 28°
60% 80% 45° 8° 16° 28°
30% 80% 45° 8° 16° 28°
80% 90% 0° 8° 16° 28°
80% 70% 0° 8° 16° 28°
80% 60% 0° 8° 16° 28°
80% 30% 0° 8° 16° 28°

FIG. 2 _ 10 b.

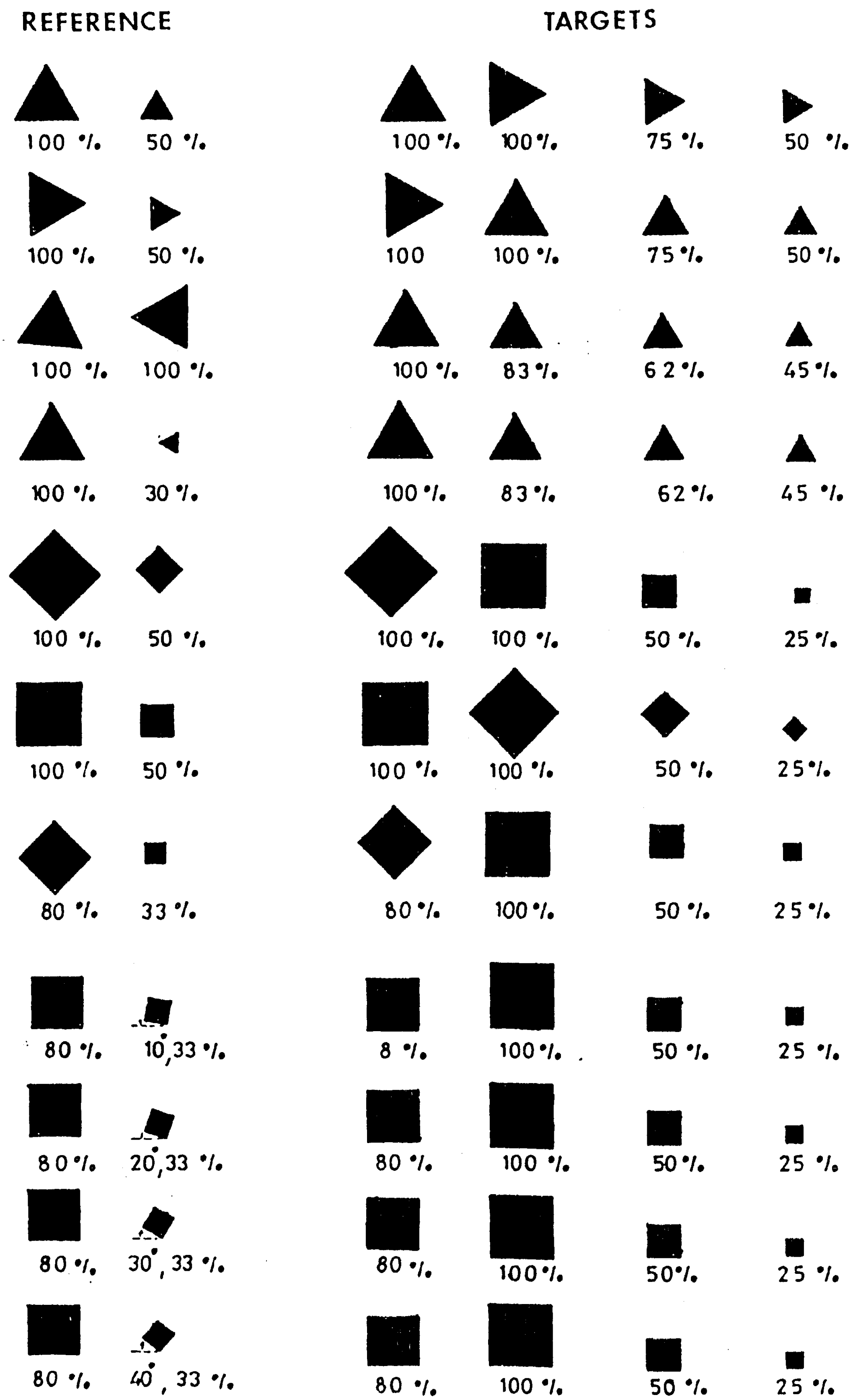
REFERENCE
TARGETS
100 % 50 % 100 % 100 % 75 % 50 %
100 % 50 % 100 100 % 75 % 50 %
100 % 100 % 100 % 83 % 62 % 45 %
100 % 30 % 100 % 83 % 62 % 45 %
100 % 50 % 100 % 100 % 50 % 25 %
100 % 50 % 100 % 100 % 50 % 25 %
80 % 33 % 80 % 100 % 50 % 25 %
80 % 10°, 33 % 8 % 100 % 50 % 25 %
80 % 20°, 33 % 80 % 100 % 50 % 25 %
80 % 30°, 33 % 80 % 100 % 50 % 25 %
80 % 40°, 33 % 80 % 100 % 50 % 25 %

FIG. 2 _ 10c

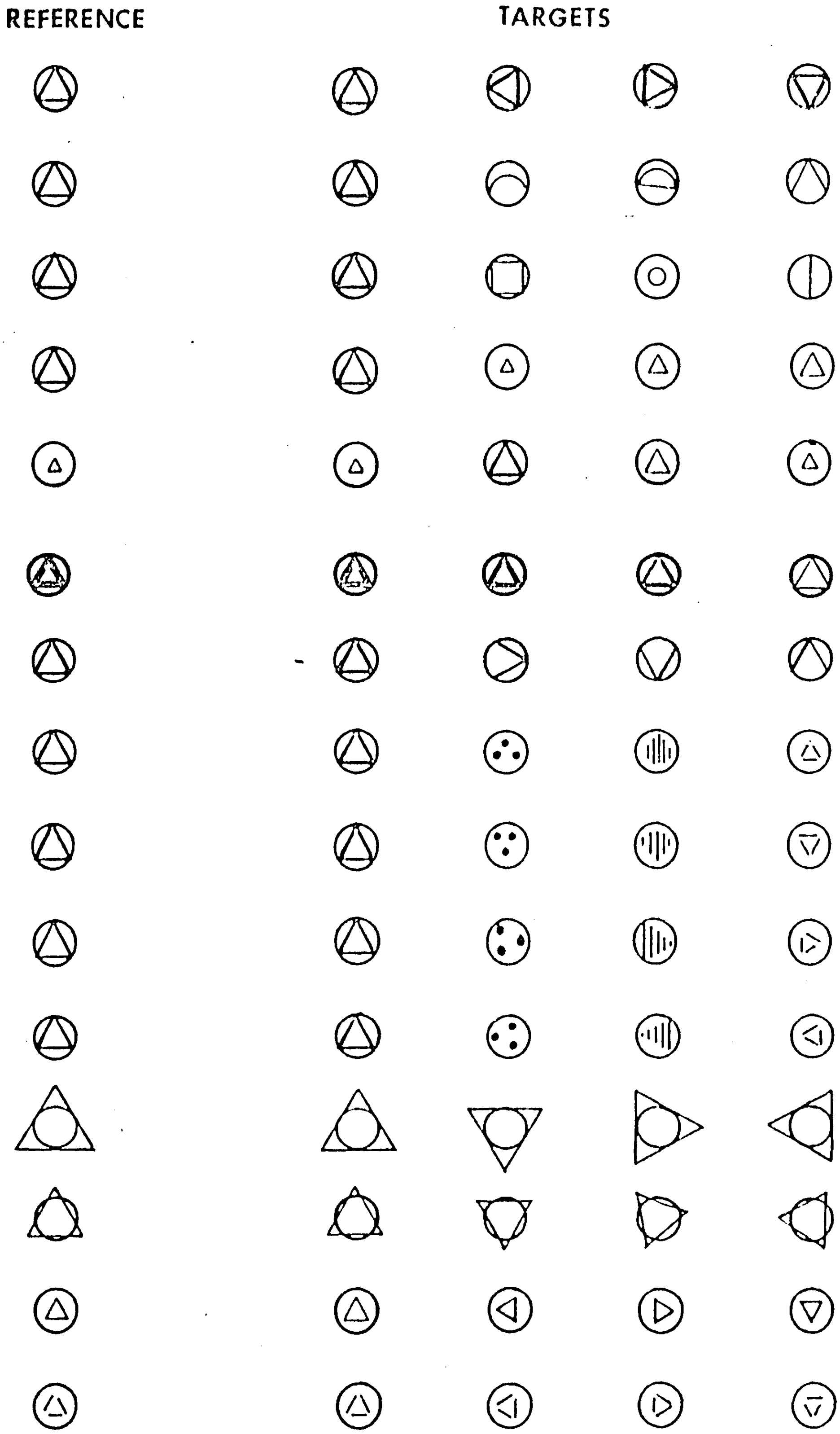

FIG. 2-11. Complex reference and targets used for discrimination of orientation and magnification. Data obtained with these stimuli are given in Figures 7-1 to 7-7.

CHAPTER THREE

Chapter Three
Spatial Discrimination with Complex Reference Fields

3.1. Introduction:

The extent to which coarse spatial analysis of the visual field is performed in parallel without sequential scanning was examined by Ibbotson et al. (1987) and Javadnia and Ruddock (1988a). They showed that a single target embedded in a reference field of multiple identical elements can be distinguished by virtue of its magnification or orientation without scanning of the field, except under certain limiting conditions. The target must be at an orientation of greater than 5 to 10 deg. relative to the reference elements in order that it can be distinguished in parallel, and target magnifications must differ in linear dimension by 10% to 20% from the reference size for parallel discrimination. These limits refer to the situation where the reference elements are all identical and the target is the only non-identical element. In real life, the visual field does not consist of identical elements, and in order to simulate more closely this situation, I have performed similar experiments with more complex reference fields. This was done by introducing a second class of element into the reference field.

In this chapter, I consider the discrimination, or detection of orientation and magnification differences, in order to asses the effects of reference field complexity on parallel processing.

3.2. Experimental Procedures:

In these experiments, the reference field was constructed from two classes of reference elements, which were randomly distributed in equal numbers. The various reference elements and the corresponding targets used in this section of the work are shown in Figs 2-4 and 2-5 in Chapter 2. As previously discussed in Chapter 2, the target is chosen and presented at random locations in the reference field. Fig 2-1 illustrates a typical display for one of the targets on the VDU monitor. Each target is displayed 25 times making a total of 100 presentations and measurements were repeated so that $T_{\frac{1}{2}}$ values refer to 50 presentations of each target. The observer replied to all of these presentations by pushing the button "Yes target detected" or "No target seen". The time of reply is recorded by the computer and from it the half time, $T_{\frac{1}{2}}$, for 50% target detection was found (Fig 2-2). Measurements were made without a fixation point, and subjects were allowed to scan the field freely. The subject was seated 1.8m away from the monitor which subtended 8.5 deg. x 6.3 deg. visual angle at the subject's eye.

In order to asses the effect of complexity in the field, measurements of $T_{\frac{1}{2}}$ were made for different numbers, N, of reference elements and the values of $T_{\frac{1}{2}}$ plotted against N. Measurements were made both with the mixed reference field and with the simple fields containing only one or other class of reference element. Comparison between the data for the two types of reference field demonstrates the effect of increasing the complexity of the reference field.

3.3. Subjects:

The subjects who participated in these experiments were all undergraduates or post-graduates at Imperial

College. They were all experienced observers and possessed at least 6/6 visual acuity when corrected with spectacles. They were three females WA, JS and JH and three males AM, DB and PM.

3.4. Results:

The results are presented in two sections, the first of which is concerned with the discrimination of orientation of (i) lines, (ii) triangles and (iii) square elements. The second section deals with the discrimination of target magnification for (i) lines, (ii) triangles and (iii) square elements. In all these experiments $T_{\frac{1}{2}}$, the time required for 50% probability of detecting the target, is plotted against N, the total number of reference elements.

3.4.1. Discrimination of Target Orientation:

(i) Lines:

In the first set of experiments, the reference field contained a mixture of two orthogonal lines (Fig 3-1) and data for two sets of target orientations are plotted in Fig 3-2 and 3-3 and refer to three subjects. Each set of data refer to a single target orientation, and data are given in each case for the mixed reference field and for simple reference fields constructed from either element alone. It is seen that results for all reference fields are similar both in magnitude and in the fact that $T_{\frac{1}{2}}$ is independent of N. The introduction of the mixed elements into the reference field gives rise to only a small increase in the values of $T_{\frac{1}{2}}$. A different response pattern is observed in Fig 3-4 however, which refers to measurements made with two line components orientated either vertically or at 40 deg. to the vertical. Again, each plot refers to a

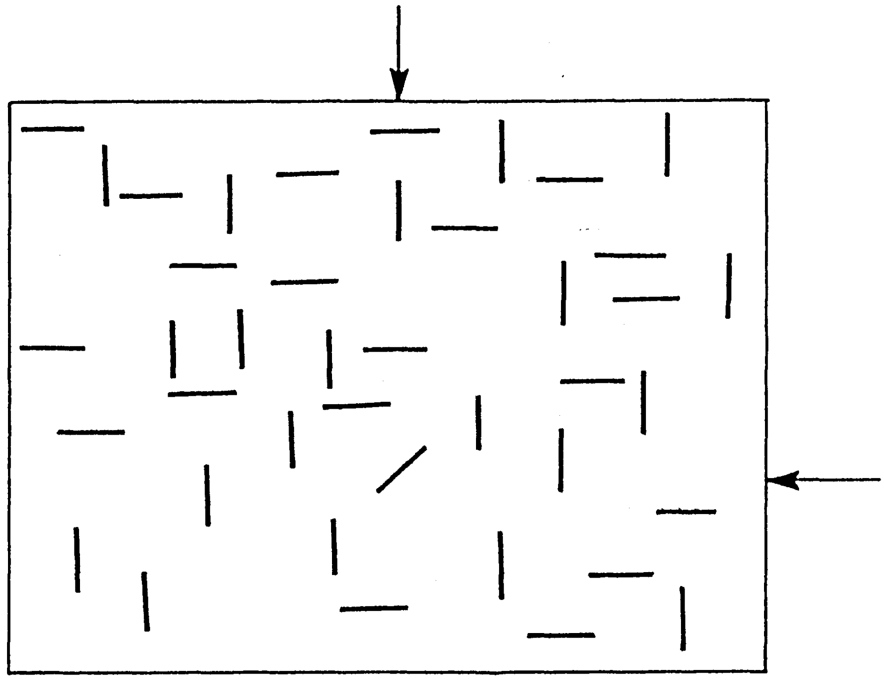

FIG. 3 _ 1 . An example of reference field composed of 20 of each of two orthogonal lines and a target; denoted by the arrows.

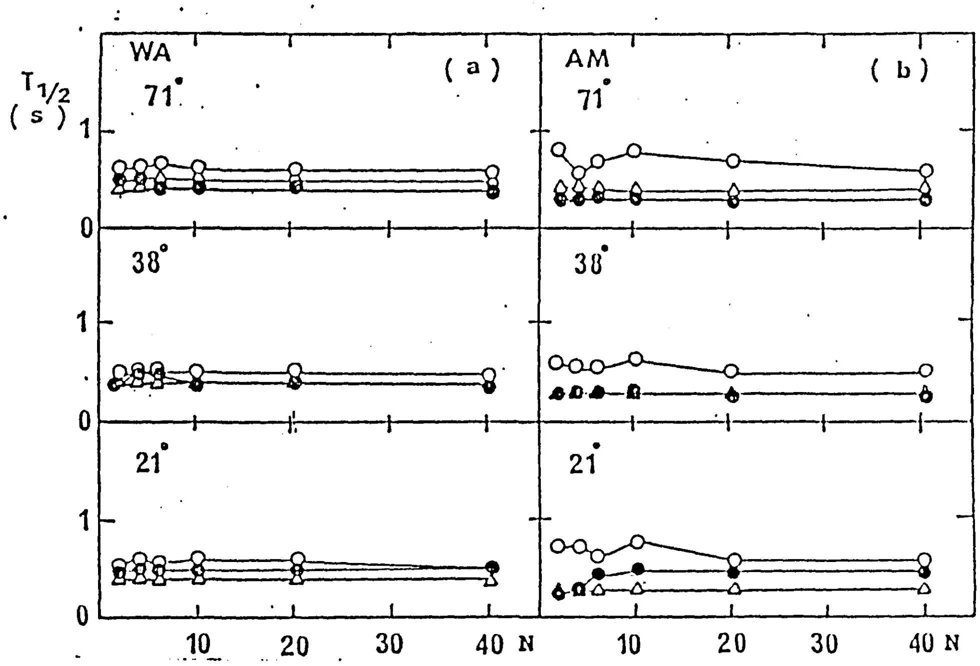

FIG. 3-2. Orientation discrimination for line elements. $T_{1/2}$ values are plotted against N, the number of reference elements, for orientation discrimination with reference fields consisting of; o, for and —; ●, for | ; and Δ for —; data are given for three line targets oriented from the vertical as labelled. Results are for two subjects (a) for WA, (b) for AM.

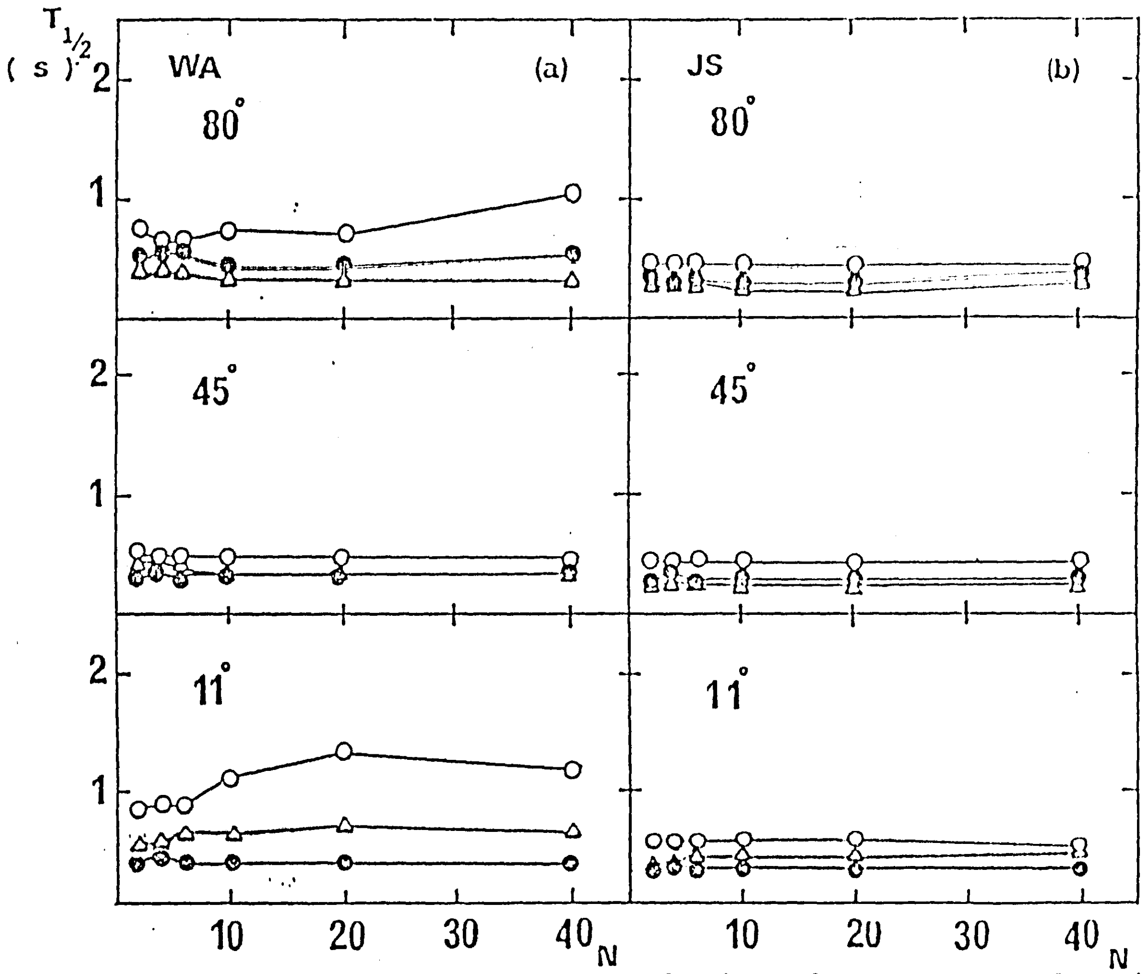

FIG. 3-3. Orientation discrimination for line elements. $T_{1/2}$ is plotted against N, the number of reference elements, with reference field consisting of line; o, for | and — ; ● for — ; and Δ for | ; for three line targets oriented as labelled on the upper left side of each plot. Results are for two subjects; (a) for WA, (b) for JS.

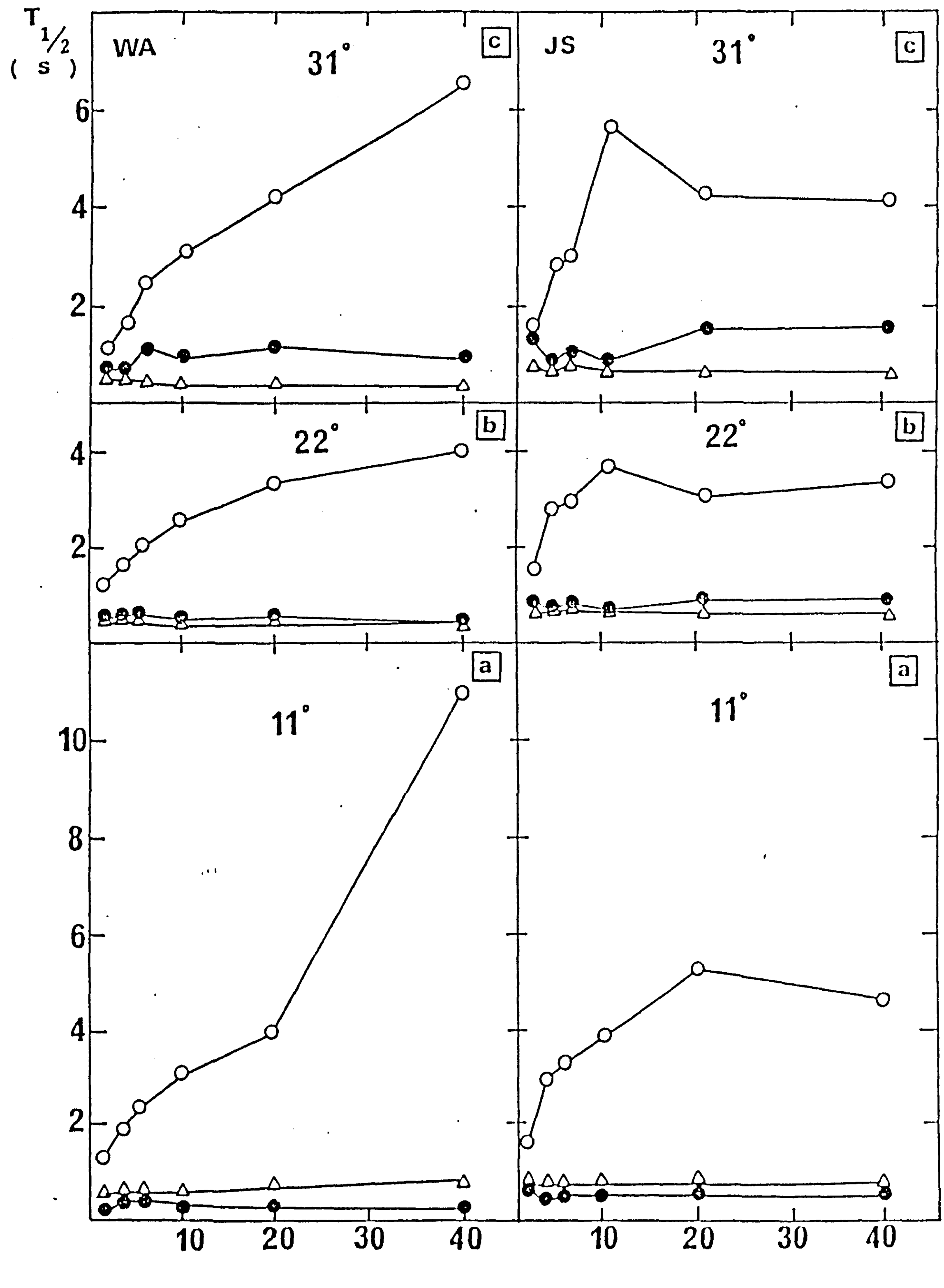

FIG. 3 - 4. Orientation discrimination for line elements, $T_{½}$ values are plotted against N for reference fields of lines with 0° and 40° orientation (○), with 40° orientation (●), and with 0° orientation (△). Each plot is for a target with orientation as marked. The linear regression coefficients for $T_{½}$ on N are for WA 11° target 0.254±0.030, 22° target 0.098±0.008, 31° target 0.137±0.0126; and for JS 11° target 0.077±0.014, 22° target 0.012±0.011, 31° target 0.024±0.023.

single target orientation and data are given for the same two subjects. For each target orientation, $T_{\frac{1}{2}}$ values for the mixed reference fields are large, and in many cases, there is a statistically significant positive correlation between $T_{\frac{1}{2}}$ and N. In contrast, $T_{\frac{1}{2}}$ values recorded for the simple reference field of each of the reference elements separately are markedly lower than those for the complex field, and are independent of N. Similar, though less marked differences between results for complex and those for simple reference fields are found when the two classes of reference elements are oriented vertically and at 60 deg. to the vertical (Fig 3-5). Thus, as the angle between the component lines of the mixed reference field is reduced from 90 deg. to 60 deg. to 40 deg. (Figs 3-2, 3-3, 3-5 and 3-4), the effects of introducing a mixture of elements into the reference field become more marked, with increase in the values of $T_{\frac{1}{2}}$, and a positive correlation between $T_{\frac{1}{2}}$ and N.

(ii) <u>Triangles:</u>

Similar measurements were made for fields consisting of equilateral triangular elements. The various elements used in these measurements are illustrated in Fig 2-4, Chapter 2.

In the first experiment to be considered, the reference field consisted of two classes of equilateral triangle, one with upright orientation and the other rotated through 30 deg., in a clockwise direction. Data for targets whose orientation angles lay between those of the two reference elements are presented in Figs 3-6 and 3-7 and refer to three subjects. In those graphs, the $T_{\frac{1}{2}}$ values obtained with the mixed reference fields are greater than those for the single reference fields,

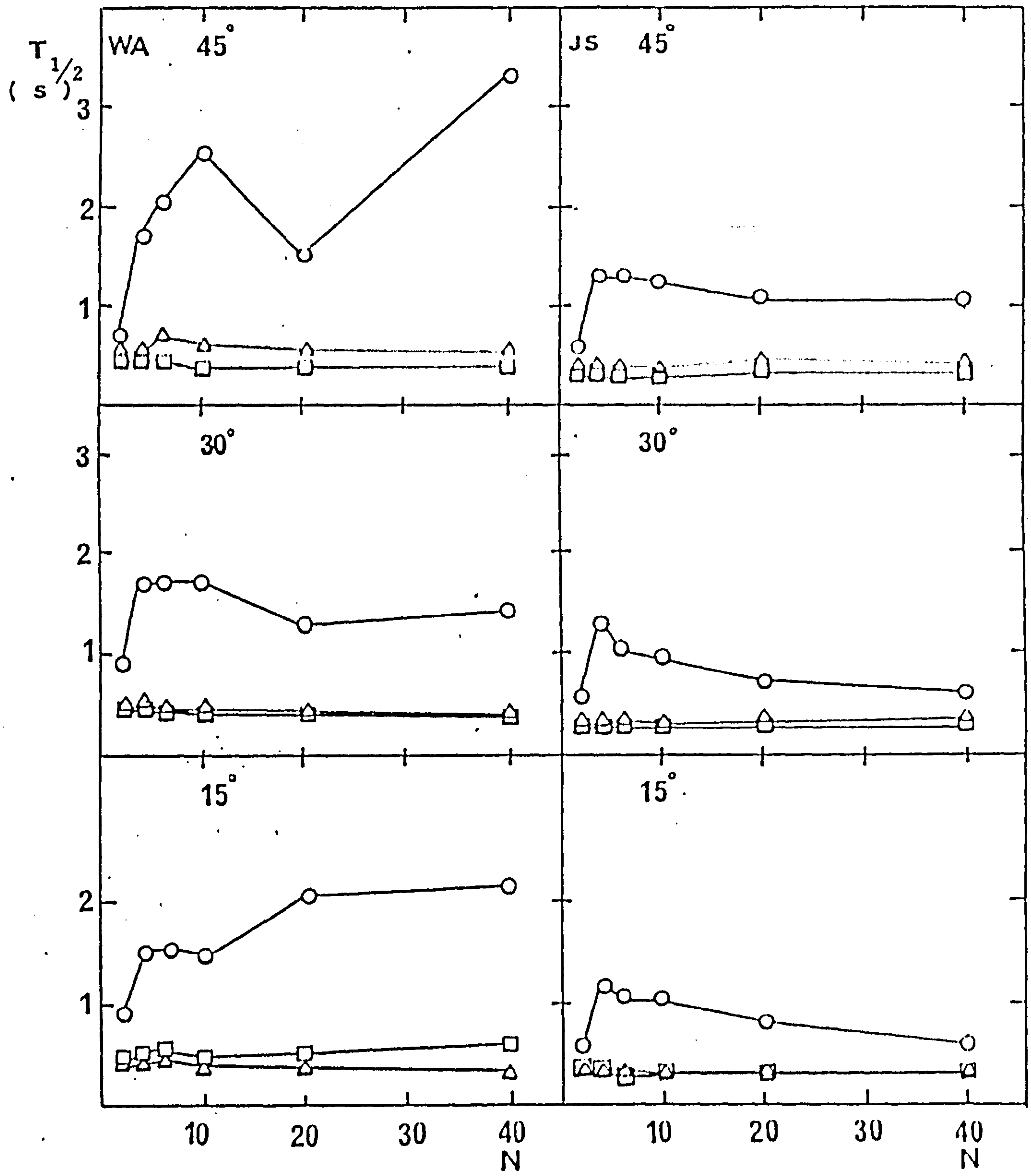

FIG. 3-5. Orientation discrimination for line elements. $T_{½}$ is plotted against N for reference fields consisting of vertical lines and lines at 60° rotation from vertical (O), vertical lines (□) and lines at 60° to the vertical (△). Targets were lines of orientation as marked on each plot. Results are for two subjects. WA results for mixed reference give positive least square linear regressuib coefficients; for 15° target 0.027±0.009, and for 45° target 0.0452±0.021.

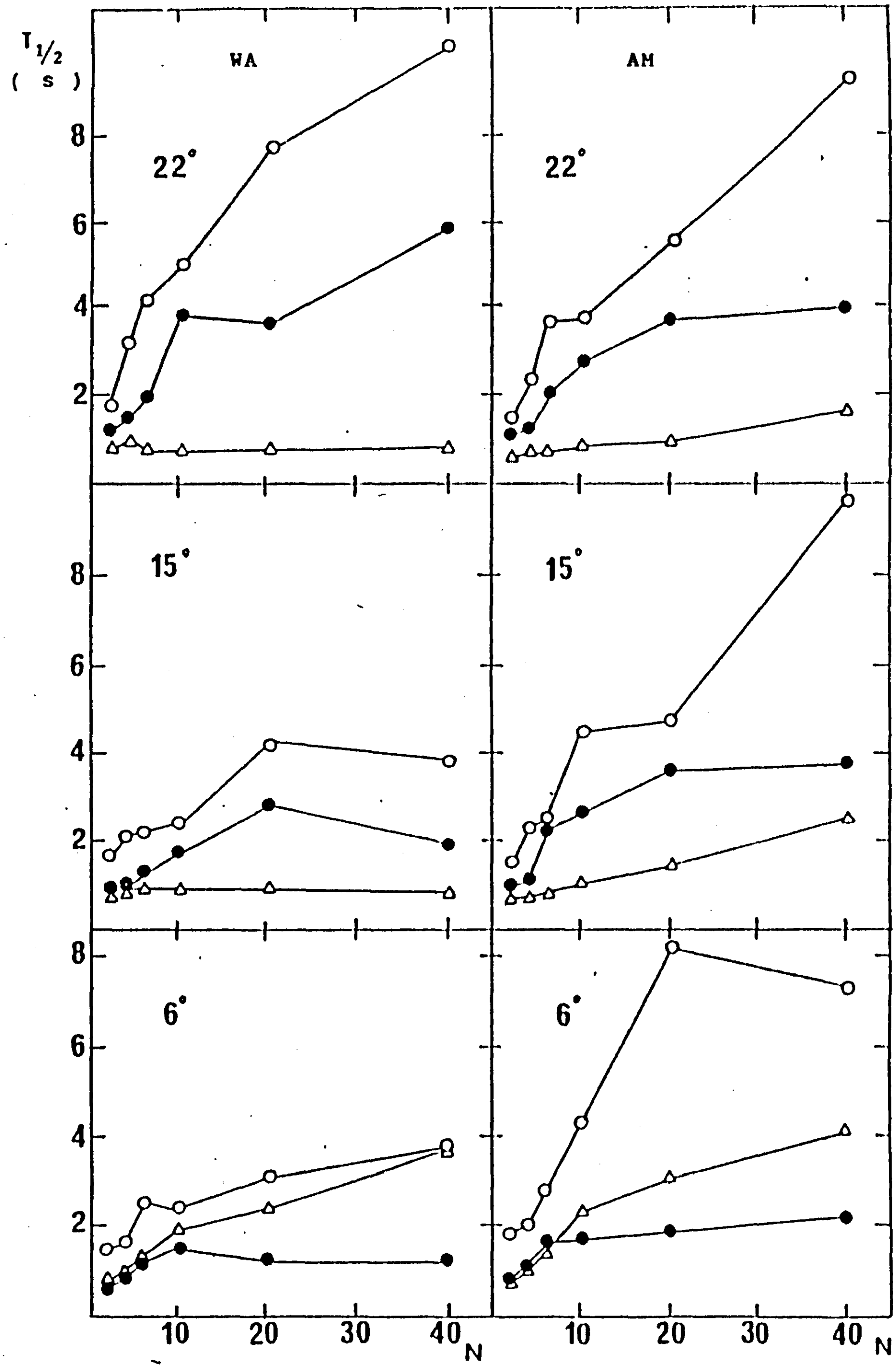

FIG. 3-6. Orientation discrimination for triangles. The reference fields were mixed elements of ▲ and ◀ (○); single reference element ▲ (△); single reference element ◀ (●). The target orientation is marked on each plot. Results are for two subjects WA and AM. Least square values give regression coefficient of (a) 6° target 0.0574±0.0126, 15° target 0.0607±0.021, 22° target 0.2069±0.030. (b) 6° target 0.163±0.0534, 15° target 0.201±0.0199, 22° target 0.192±0.0162.

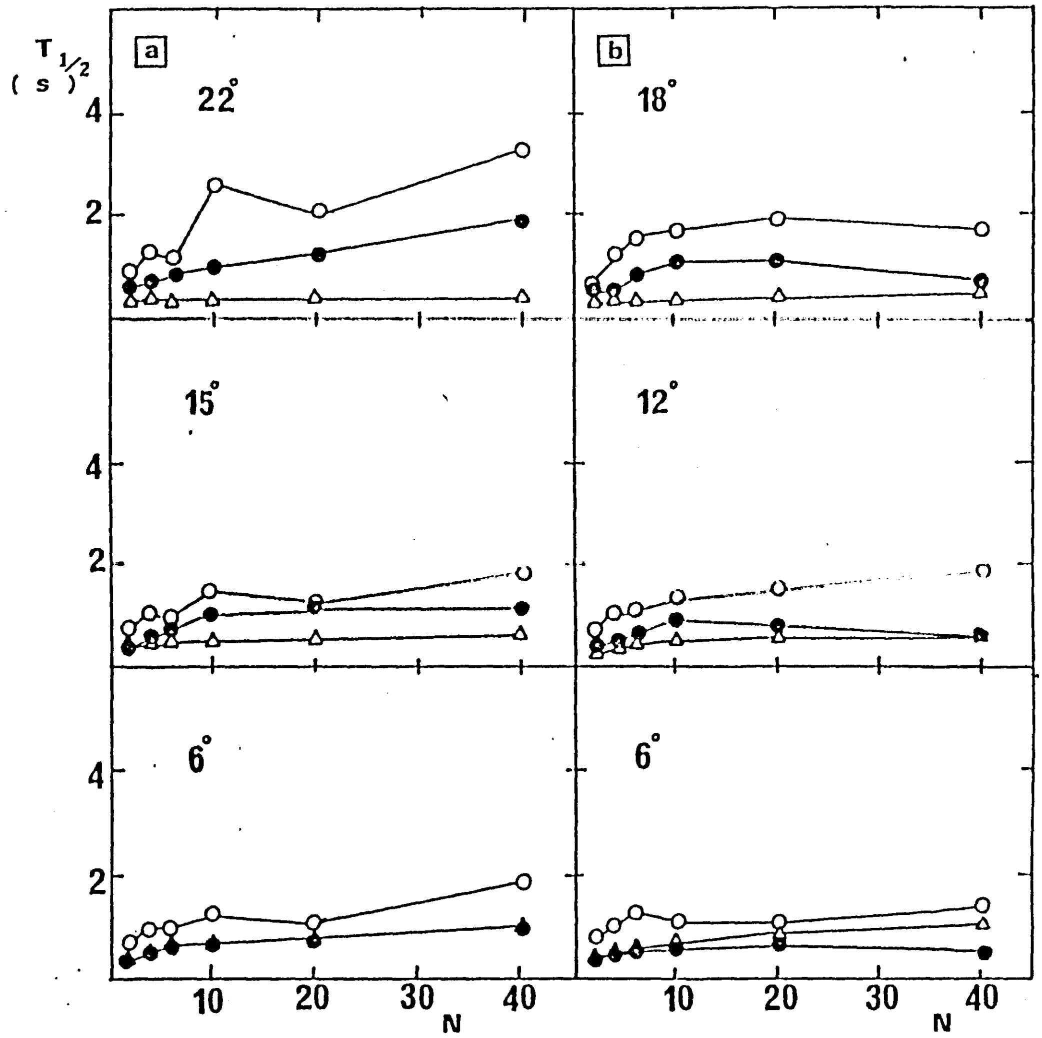

FIG. 3-7. Orientation discrimination for two triangular elements for one subject, with target orientation specified in each plot. Reference elements are; ▲ ◀ (○); ▲ (△); and ◀ (●). Least square analysis give regression coefficients of (a) 6° target 0.0257±0.0049, 15° target 0.0226±0.0064; 22° target 0.0553±0.0031; 18° target 0.0221±0.0027.

and in some cases there is clear transition from parallel to non-parallel processing as the field changes from single to mixed reference elements (e.g. Fig 3-7.b 12 deg. target). Subject JS appeared less affected by the mixed reference fields than the other subjects.

Results were obtained also for the same orientations of reference and target elements which were half the size of those used for the previous experiment (linear dimension of 0.27 deg. compared to 0.50 deg.) and the resulting $T_{\frac{1}{2}}$ values are shown in Fig 3-8 for two subjects. The result obtained is similar to that of the larger equilateral triangles, in that $T_{\frac{1}{2}}$ values are greater for the mixed reference fields than those for the single reference fields, and the effect is in this case more marked for subject JS. The difference between data for the mixed and simple background fields is less marked with the smaller elements, because in many cases the values of $T_{\frac{1}{2}}$ vary with N even for the simple reference fields consisting from one class of elements.

All the elements used in the previous experiments were (blocked) green, and for comparison, measurements were performed with the other colours of the elements (larger sized triangle) such as yellow, blue and red. The results obtained are shown in Fig 3-9 performed by two subjects for blue elements, and Fig 3-10 for yellow elements. Fig 3-11 show $T_{\frac{1}{2}}$ values obtained with the mixed reference elements for all three target orientations for red elements for comparison with the data for green elements. The form of the results for these different colours is similar to that found for the green elements discussed previously, thus the colour of the elements is not an important consideration in these experiments.

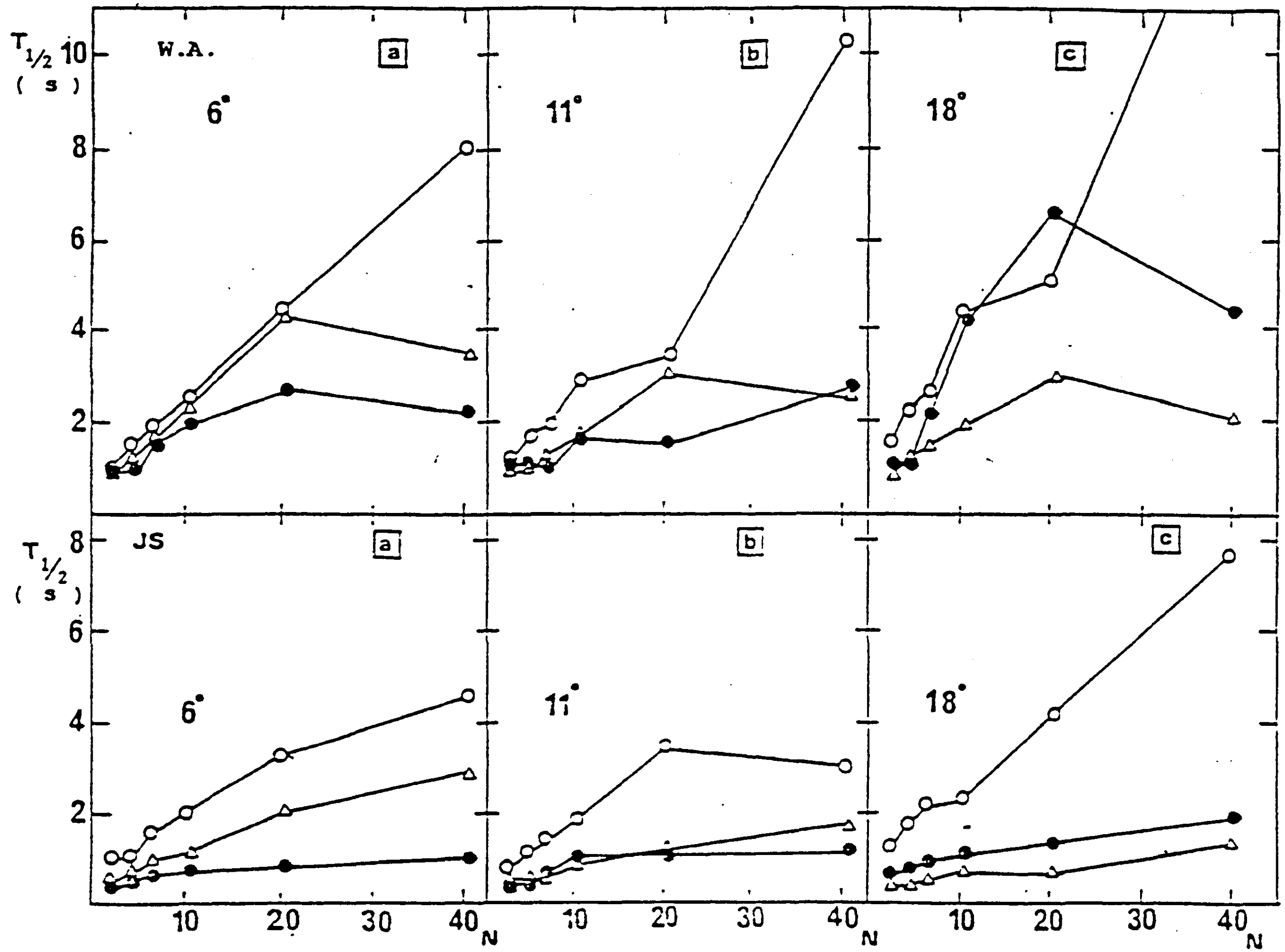

FIG. 3-8. Discrimination measurements for triangular elements. Results are for two subjects, WA and JS. Reference fields were ▲ and ◀ (○), ▲ (△) and ◀ (●). Least square analysis for WA five regression coefficient, 6° target 0.182±0.0041, 11° target 0.227±0.0284, 18° target 0.345±0.0393 and for JS; 6° target 0.0971±0.009, 11° target 0.59±0.0195, 18° target 0.1689±0.0069.

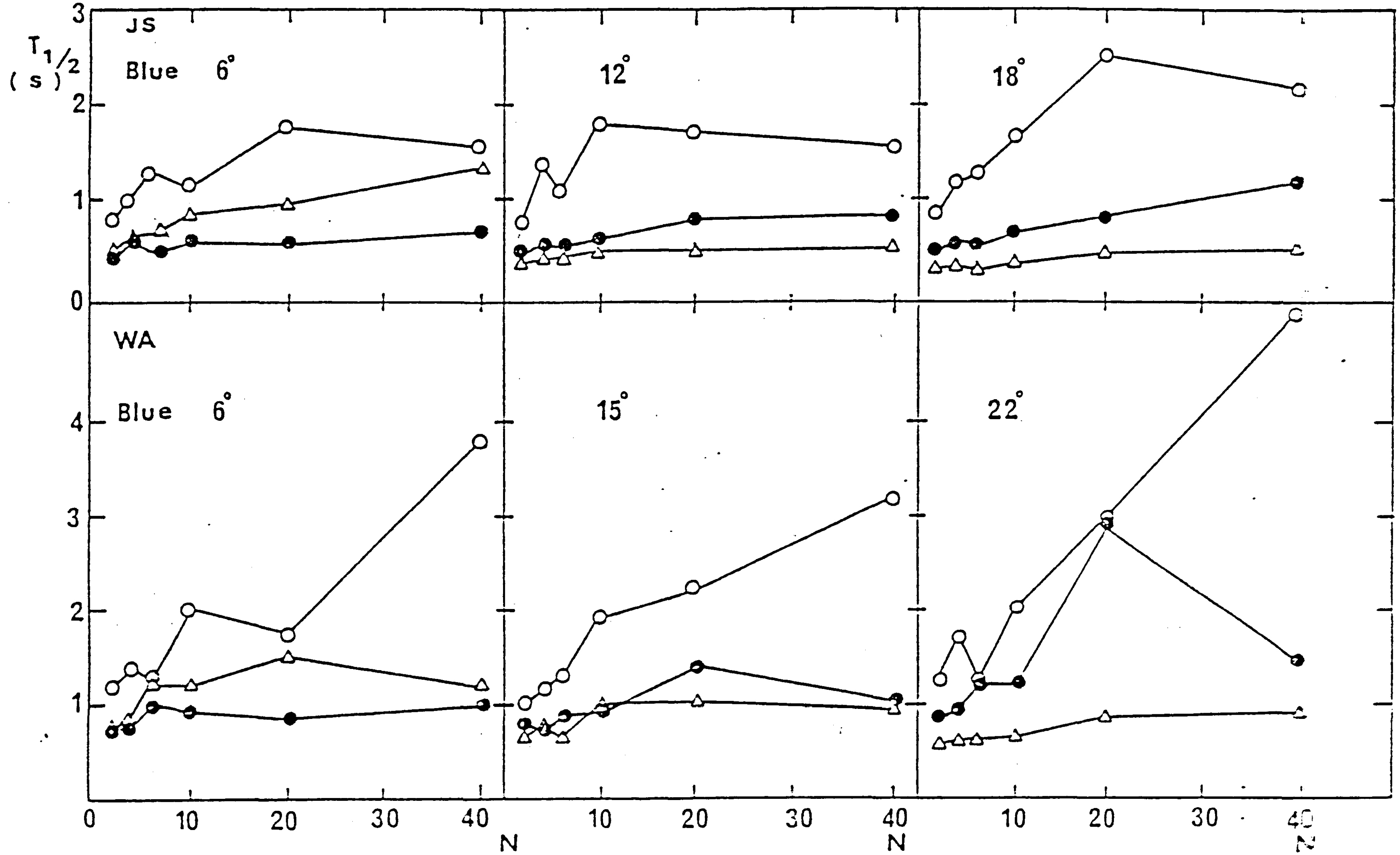

FIG. 3-9. Orientation discrimination for triangular elements (coloured blue). The target orientation is marked on each plot. Results are given for two subjects. The reference fields were mixed elements ▲ and ◀ (○), ▲ (△) and ◀ (●).

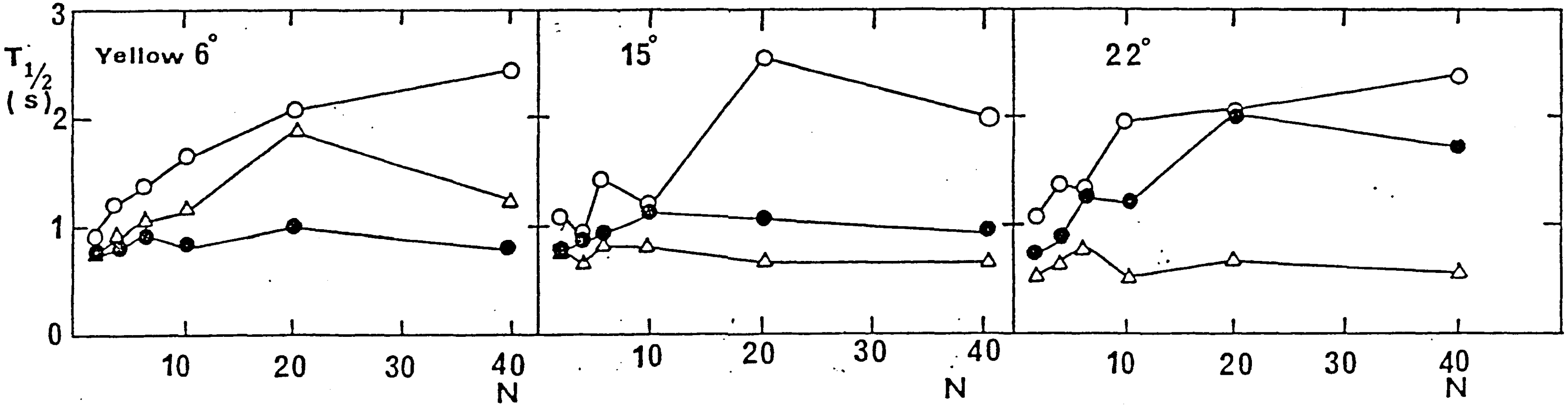

FIG. 3 – 10. Orientation discrimination for yellow trinagular elements. The target orientation is marked on each plot. Data for reference fields ▲ and ◀ (○), ◀ (●) and ▲ (△).

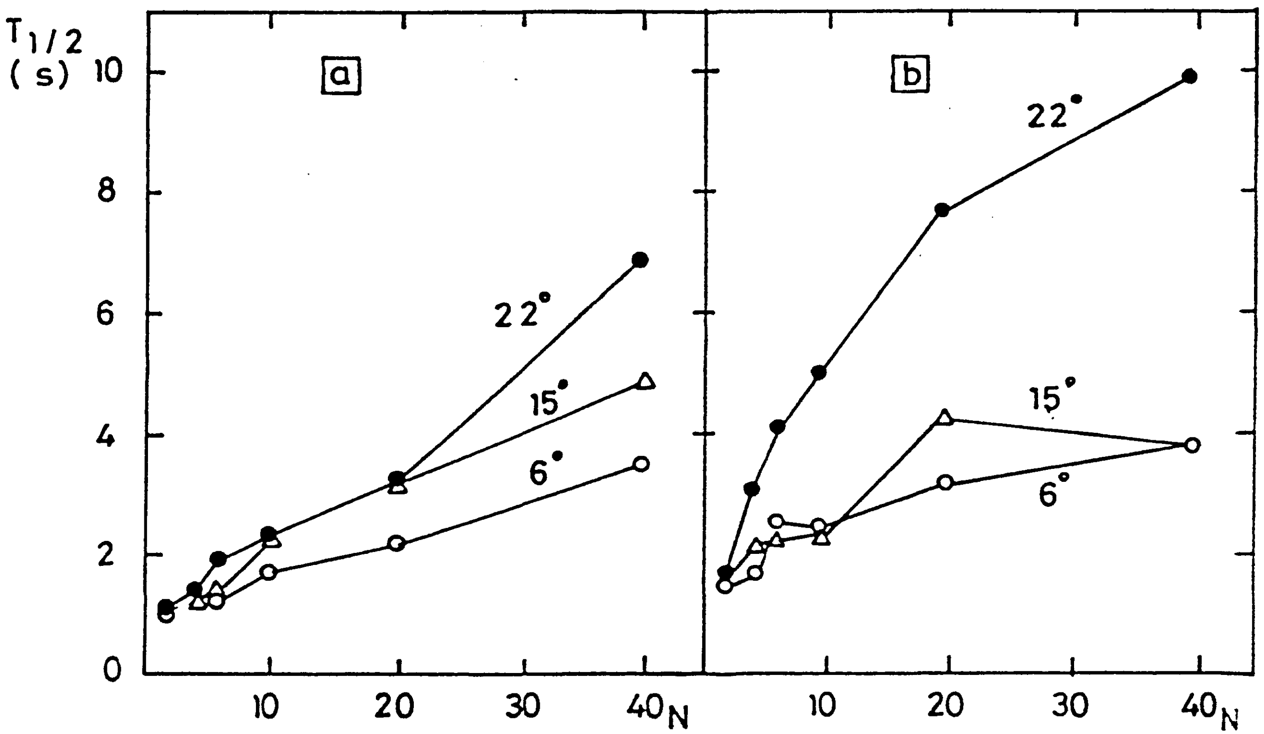

FIG. 3 – 11. Orientation discrimination for triangular elements for reference field ▲ and ◀ with the target orientation given on each line, for red coloured triangles (a), as compared with green coloured triangles (b).

Some further data were obtained in experiments for which the target orientation lay in some cases outside the range covered by the two reference elements. Fig 3-12 shows two sets of results obtained with different target orientations. It is clear that the values of $T_{\frac{1}{2}}$ obtained with the mixed reference fields are again greater than those for the simple reference fields. It should be noted, however, that the mixed reference field has less effect when the target lies outside the range of orientation covered by the reference elements.

(iii) <u>Squares:</u>

Measurements of orientation discrimination were also made with square elements. The two classes of reference element were orientated vertically and at 45 deg. to the vertical, which is the maximum possible angular difference available for such elements (Fig 2-4). All the target orientations fall in the range which is within the 45 deg. difference range of the two classes of reference element. An example of the field is shown in Fig 3-13. The data are plotted separately for each target orientation in Fig 3-14 and show very clearly that $T_{\frac{1}{2}}$ values for the mixed reference fields are greater than those for the simple reference fields constructed from a single element. Further, for the mixed fields, $T_{\frac{1}{2}}$ varies significantly with N, whereas for the simple fields, it is in all cases independent of N, corresponding to parallel processing and as shown by Javadnia and Ruddock (1988a).

Similar experiments were performed with elements of other colours and the data show that similar results are obtained, independently of the colour of the element (Figs 3-15 and 3-16).

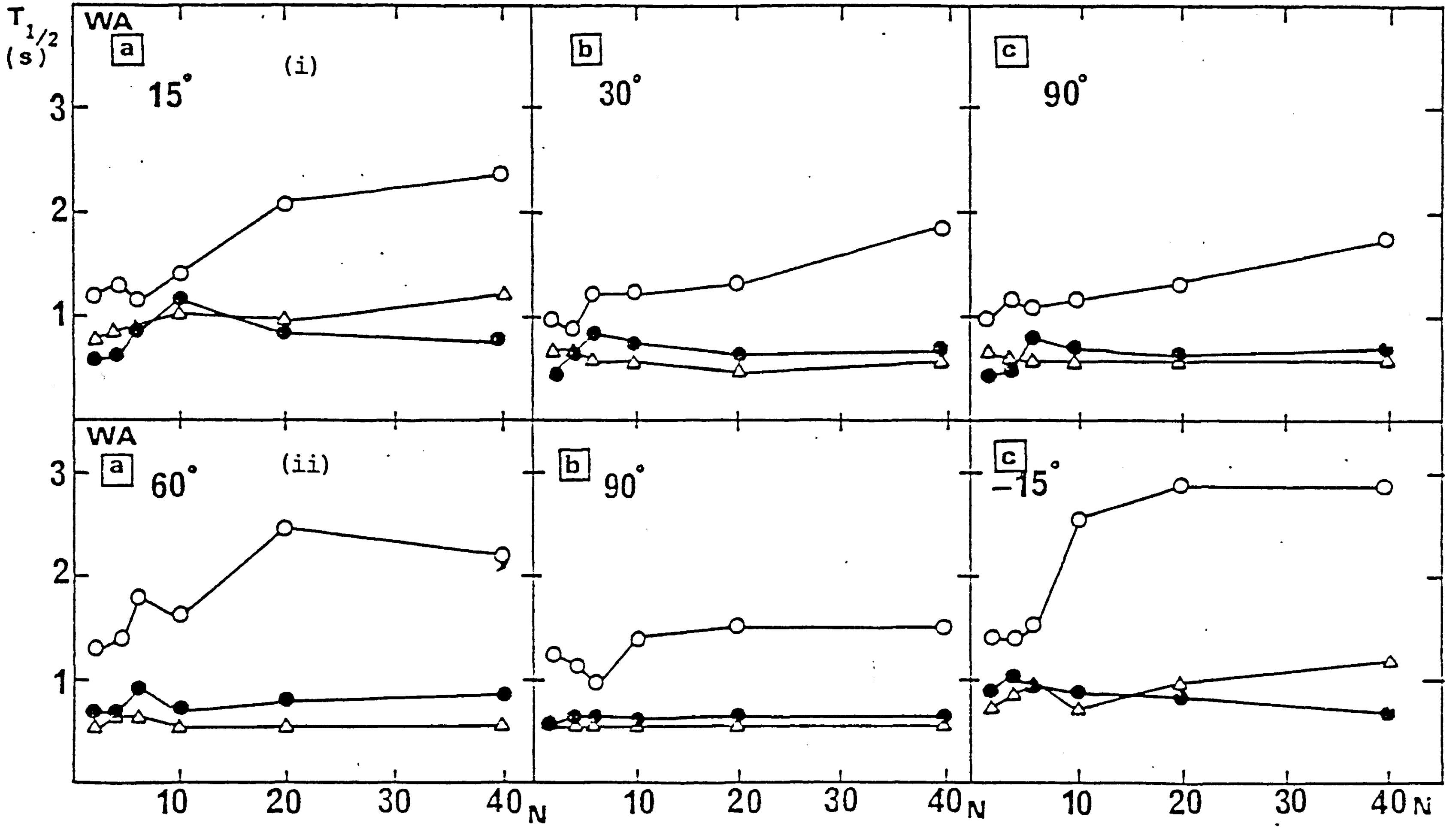

FIG. 3-12. Orientation discrimination for triangular elements with the target orientation given with each plot. (i) For reference fields ▲ and ▼ (○), ▲ (△) and ▼ (●). Least square analysis for mixed reference fields: 15° target 0.0399±0.0067, 30° target 0.0231±0.004 and 90° target 0.0185±0.0018. (ii) For reference fields ▲ and ◀ (○), ▲ (△) and ◀ (●). Least square values for mixed reference fields: 60° target 0.023±0.0102, 90° target 0.011±0.0058 and -15° target 0.040±0.0149.

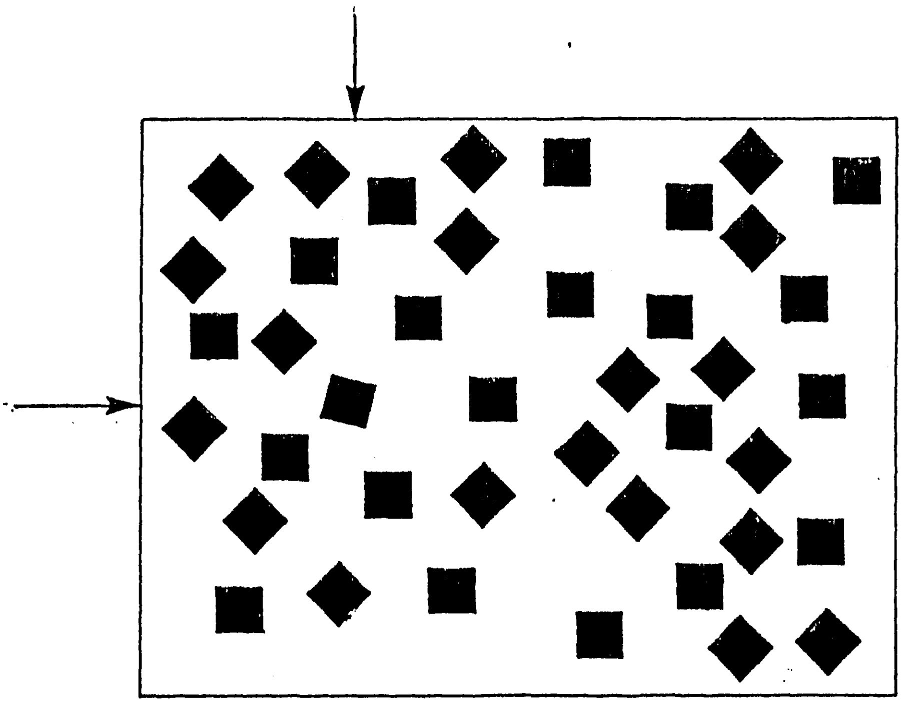

FIG. 3-13. A typical display for orientatin discrimination measurements with square shaped elements. The target is denoted by the arrow.

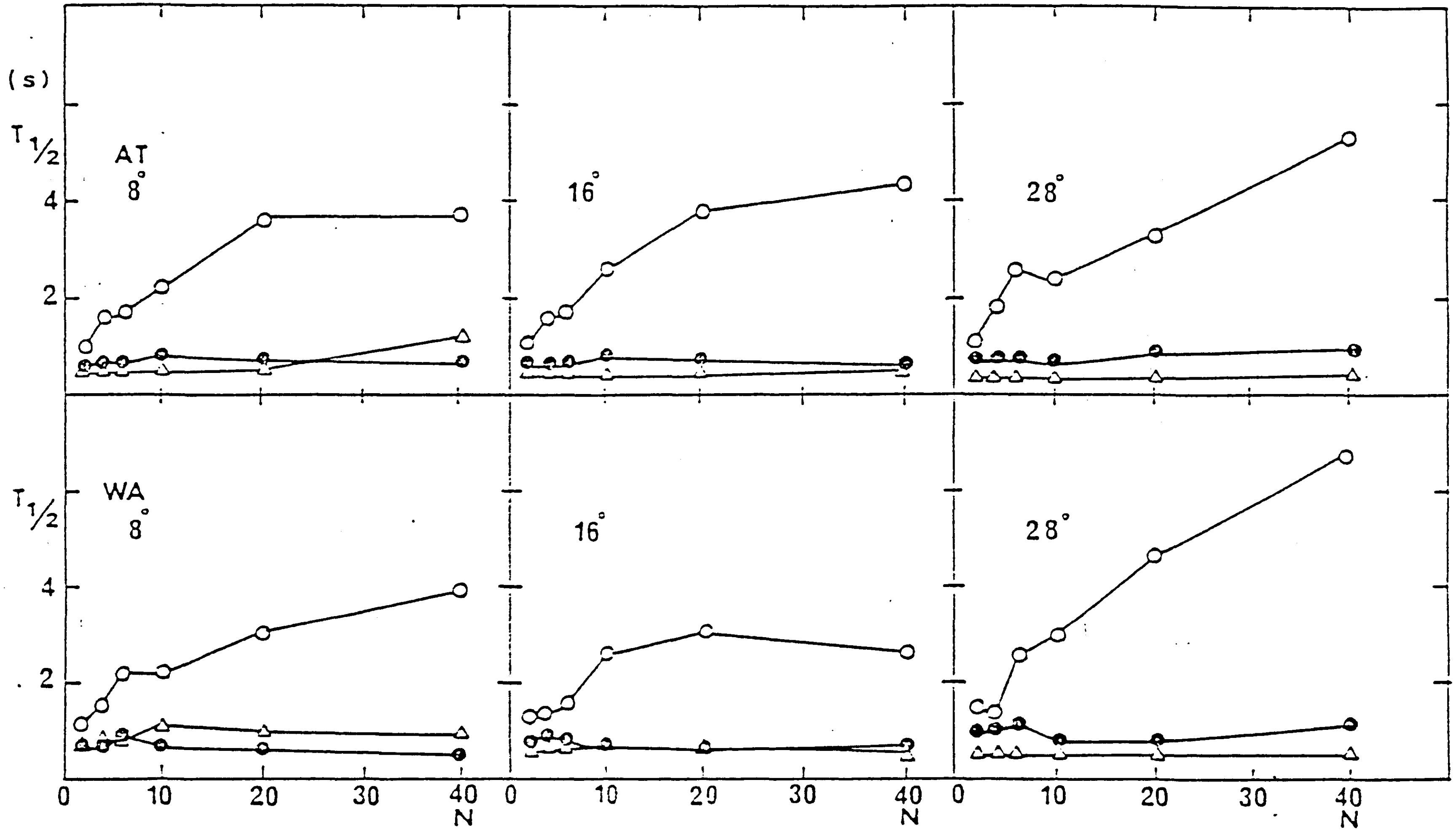

FIG. 3-14. Orientation discrimination for square elements with the target orientation marked on each plot. The reference fields were ■ and ◆ (○), ■ (△), ◆ (●). Least square regression coefficients for the mixed reference fields were: 8° target 0.066±0.011, 16° target 0.037±0.0187 and 28° target 0.142±0.0144 for subject WA; 8° target 0.071±0.018, 16° target 0.086±0.017 and 28° target 0.098±0.0127 for subject AM.

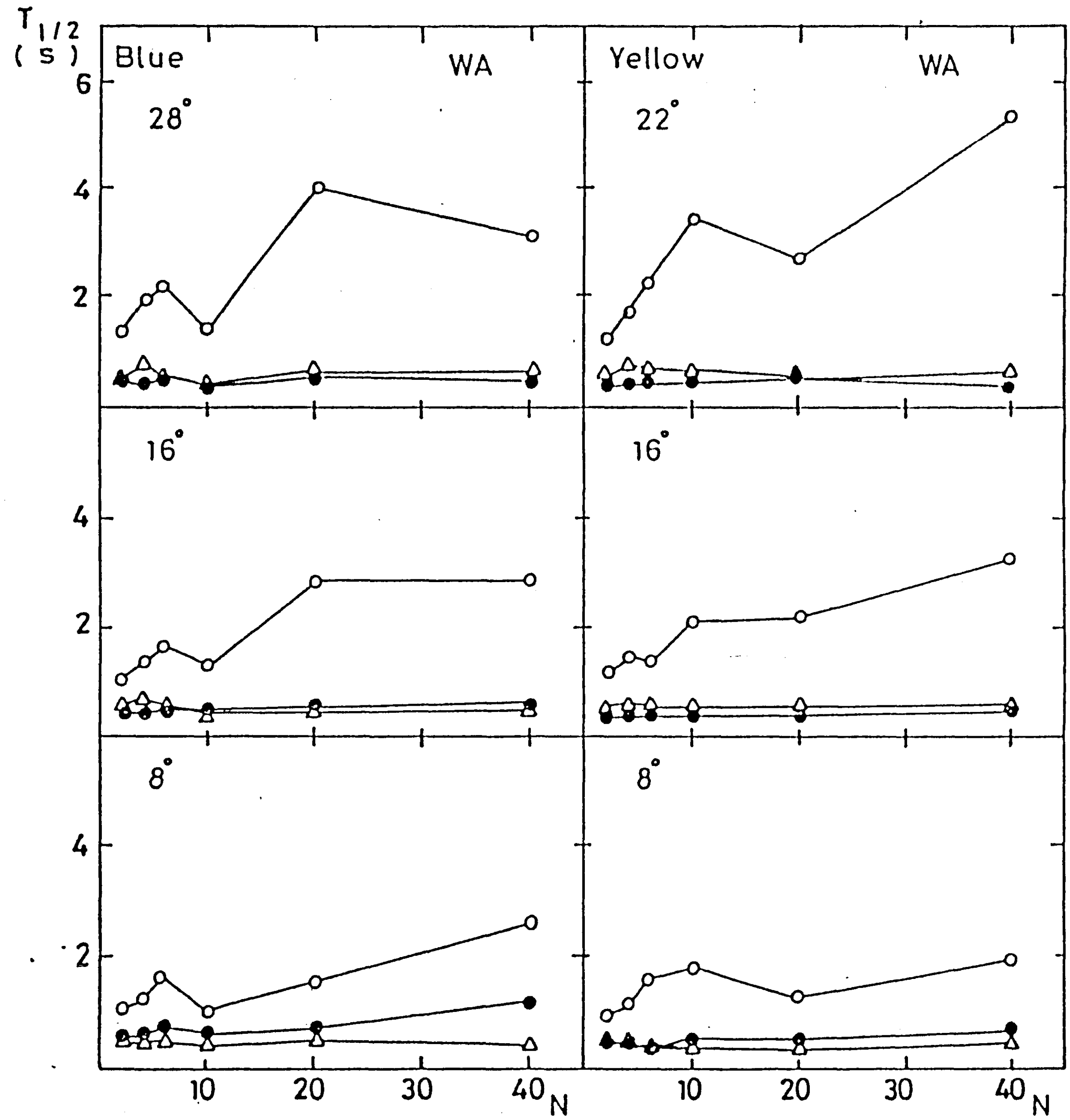

FIG. 3-15. As in Figure 3-14, but for blue or yellow coloured squares. The reference fields were ■ and ◆ (○), ■ (●), and ◆ (△).

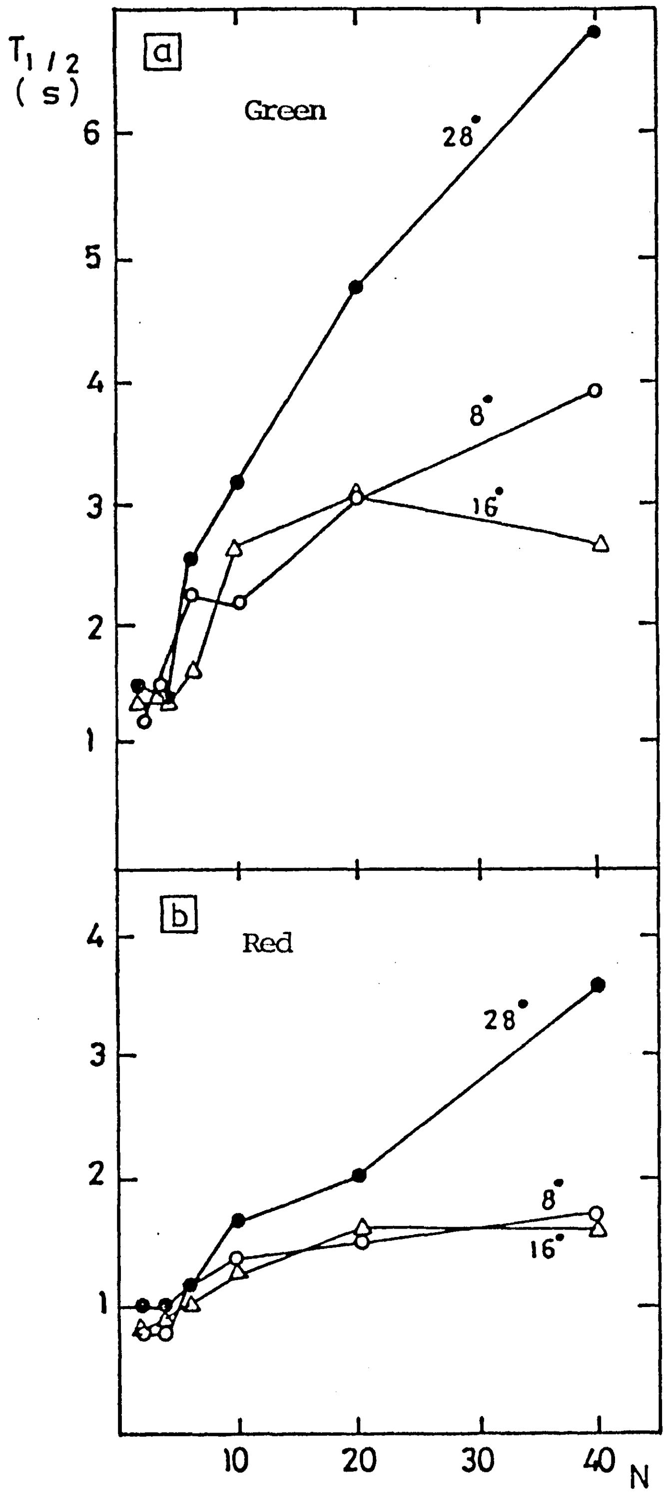

FIG. 3-16. Orientation discrimination for square elements with the target orientation labelled on each line, for reference fields of ■ and ◆ and red elements (b) as compared with green elements (a).

3.4.2. Discrimination of Target Magnification:

Magnification discrimination was measured for lines, triangles and squares, and the results are presented separately for each type of element. The size of the targets are defined in terms of relative (%) linear magnification.

(i) Lines:

In all of the experiments the targets were of relative length 100%, 50% or 25%, and measurements were made for various pairs of reference elements, (see Fig 2-5). All the targets and reference elements were oriented vertically, (see Fig 3-17 for a sample field).

The results obtained with reference elements of relative length 80% and 35% are given in Fig 3-18. It is clear from this graph that $T_{\frac{1}{2}}$ increases with the increase in the number of reference elements for the mixed reference field, as well as for one or the other of the simple reference field, and the values of $T_{\frac{1}{2}}$ are greater for discrimination against a reference field of mixed elements than against a reference field composed of a single class of element.

Another set of data is given, Fig 3-19, for reference elements of relative length 60% and 40%. For the 50% target, the values of $T_{\frac{1}{2}}$ increase greatly for the mixed reference elements, and because of the choice of reference elements, it increases also for both the simple reference fields composed of one class of reference element. For the 25% target, $T_{\frac{1}{2}}$ increases for the mixed reference elements and for one of the simple reference field, as is the case for the previous data in Fig 3-18. The data for the target of 100% relative

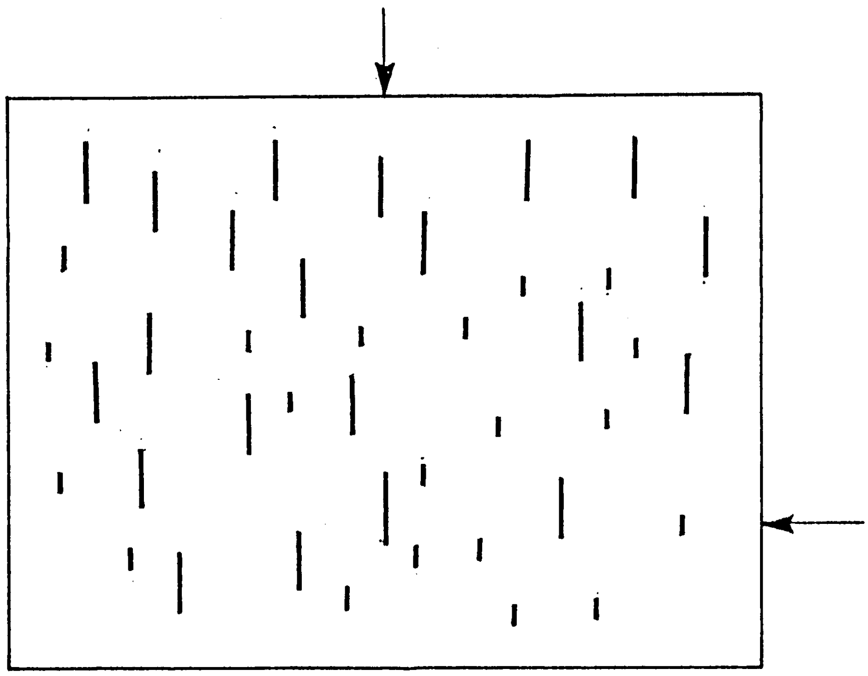

FIG. 3 – 17 . An example of a reference field consisting of two classes of line elements, of linear sizes of 80% and 33%, and a 100% target marked by the arrows.

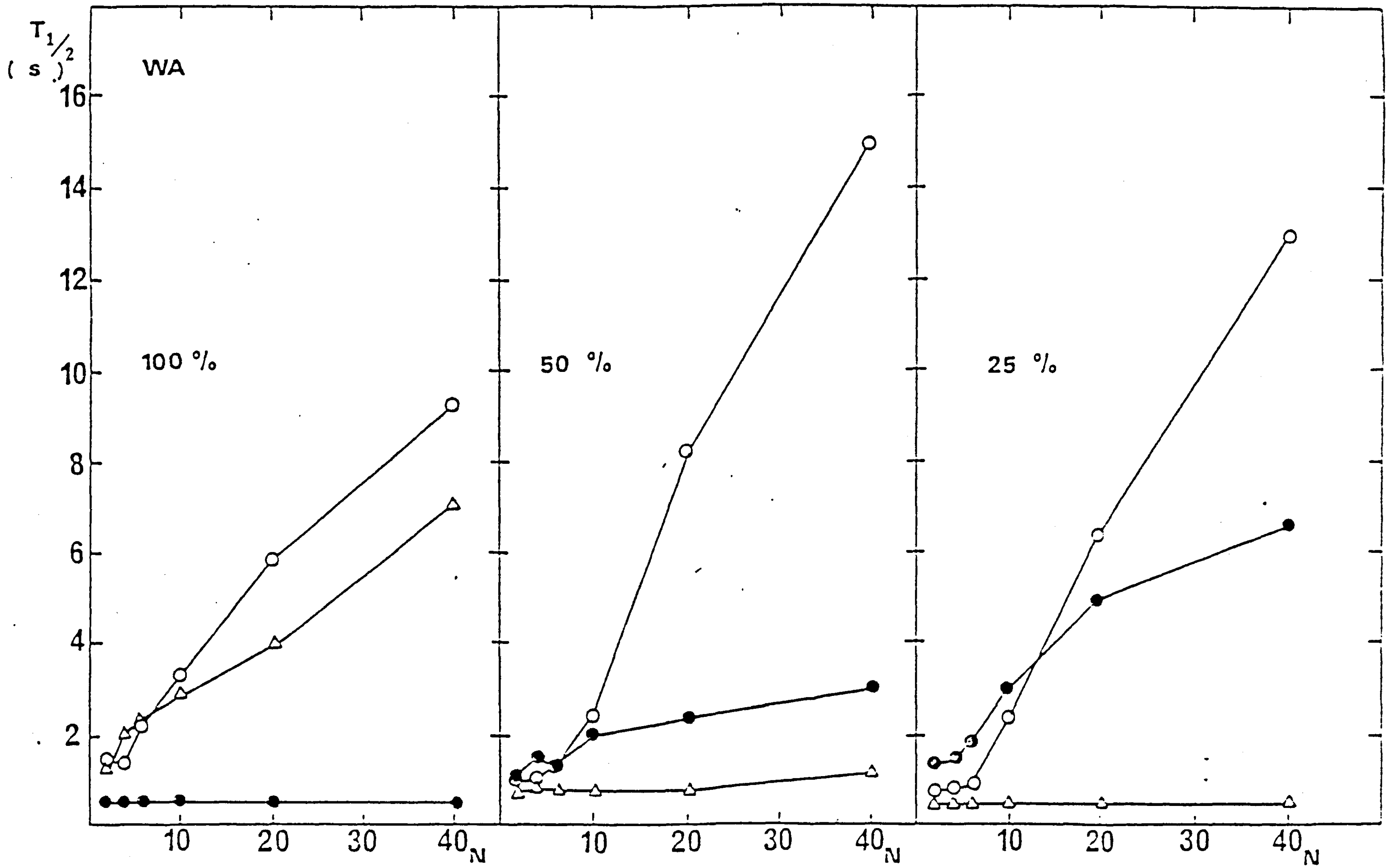

FIG. 3-18. Magnification discrimination for vertical lines with the target size marked on each plot. The reference elements were of size 80% and 35% (○), 80% (△), 35% (●). Least square regression coefficients for the mixed reference fields were 0.214±0.0122 (100% target), 0.392±0.254 (50% target) and 0.339±0.0152 (25% target).

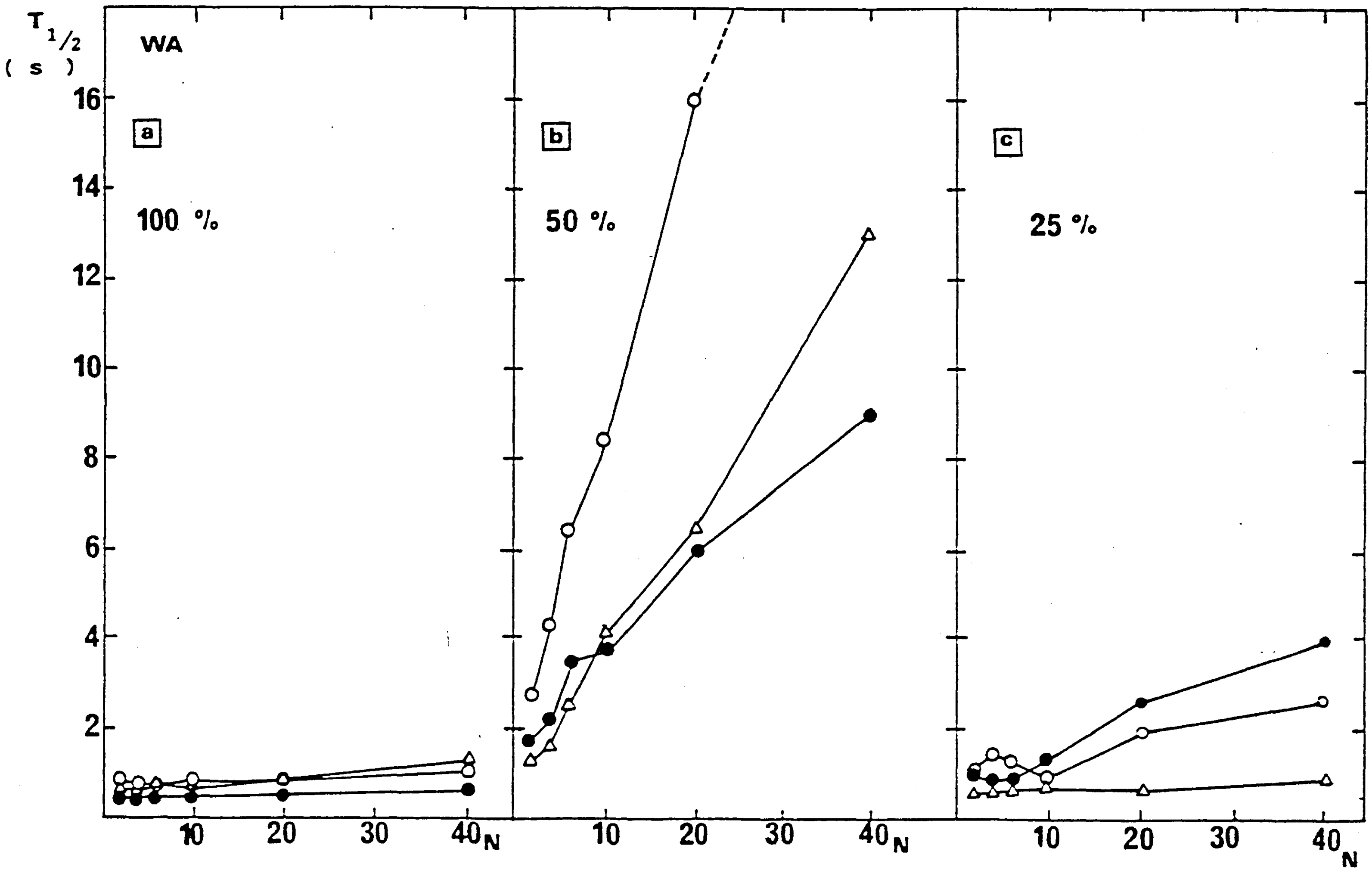

FIG. 3 – 19. Magnification discrimination for vertical lines with the target size marked on each plot. The reference element were of size 60% and 40% (○); 40% (●) and 60% (Δ). Least square regression coefficient for the mixed reference fields are : 0.0064±0.0017 (100% target), 0.723±0.028 (50% target) and 0.042±0.0095 (25% target).

length, Fig 3-19, shows that $T_{\frac{1}{2}}$ does not increase with the increase in the number of reference elements. This shows that when the target length is much greater than the length of either class of reference element, discrimination is no more difficult against the mixed than against the simple reference fields, and is parallel in all cases.

(ii) <u>Triangles:</u>

The triangular elements were all oriented upright (see Fig 2-5) and the side length of the targets were 100%, 50% or 25%, and two sets of reference element sizes were examined (see Fig 3-20 for a sample field). The data for the first set of reference elements, which were of linear size 83% and 33%, are given in Fig 3-21. The data shows the results for two subjects, and are plotted separately for each target size. $T_{\frac{1}{2}}$ values for discrimination of the target against the mixed reference fields are always greater than those for either of the simple reference fields. Further, for the mixed reference field, $T_{\frac{1}{2}}$ varies significantly with N, which is also true for measurements made with only one class of reference element, except for the 50% target. In this case, discrimination of the target was always parallel for a single class of reference element, while for the mixed reference field it was markedly non-parallel.

The second set of measurements were made with 60% and 40% reference elements. The results are shown in Fig 3-22 and data are plotted for each target separately. In this case it is clear that the process of discrimination is parallel for the 100% and the 25% targets for the mixed reference elements as well as for fields consisting of one class of reference elements.

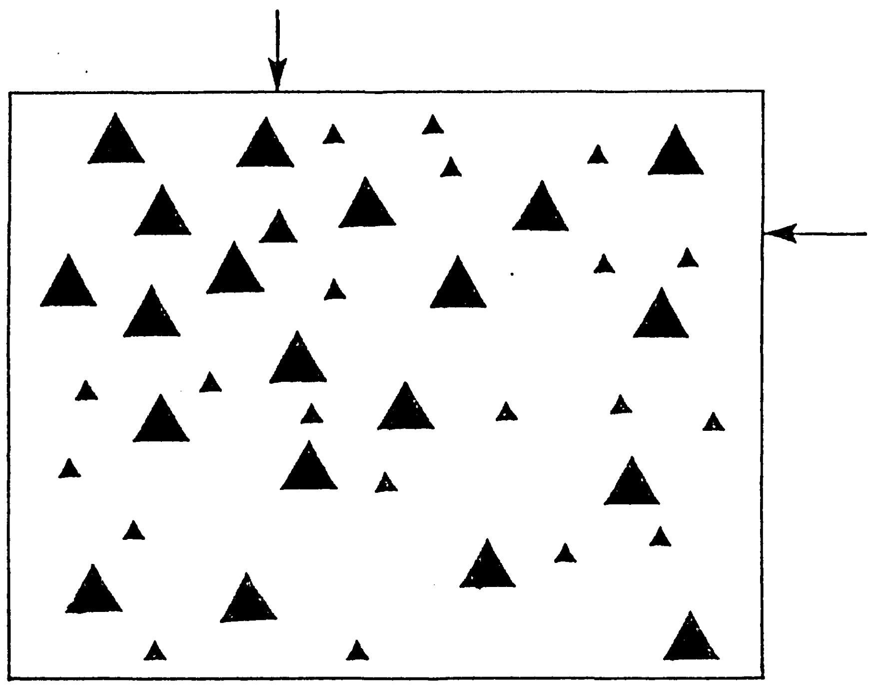

FIG. 3-20. An example of a reference field of two classes of equilateral triangular elements which differed in size, with a target of a different size marked by arrows.

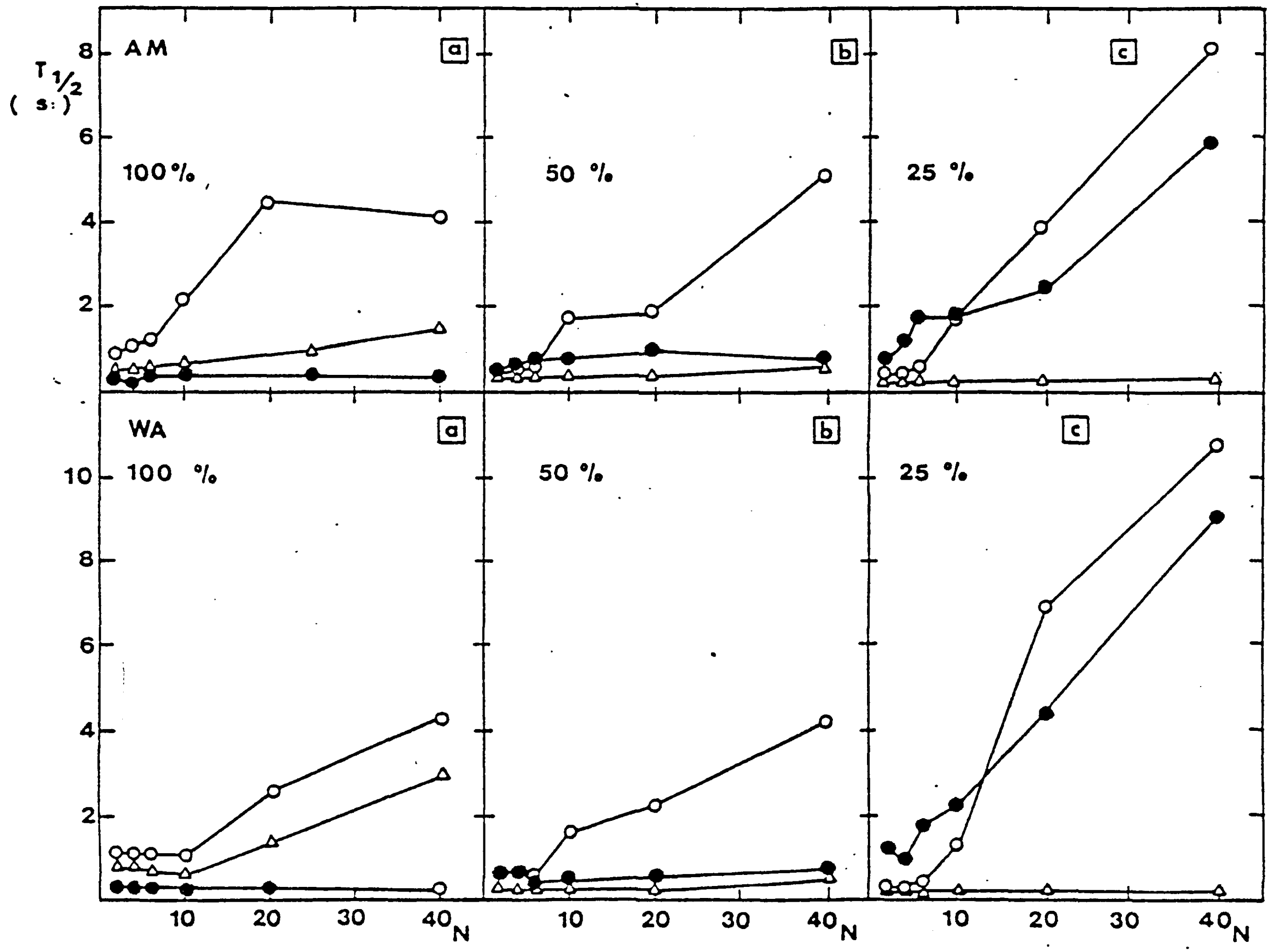

FIG. 3-21. Magnification discrimination for triangular elements for two subjects. The target size is given with each plot. Reference elements were of size 83% and 33% (○), 83% (△) and 33% (●). Least square regression coefficients for WA with the mixed reference fields are: 100% target 0.089±0.0081, 50% target 0.098±0.0076, 25% target 0.307±0.0333; for AM 100% target 0.094±0.0281, 50% target 0.119±0.0130, 25% target 0.211±0.0082.

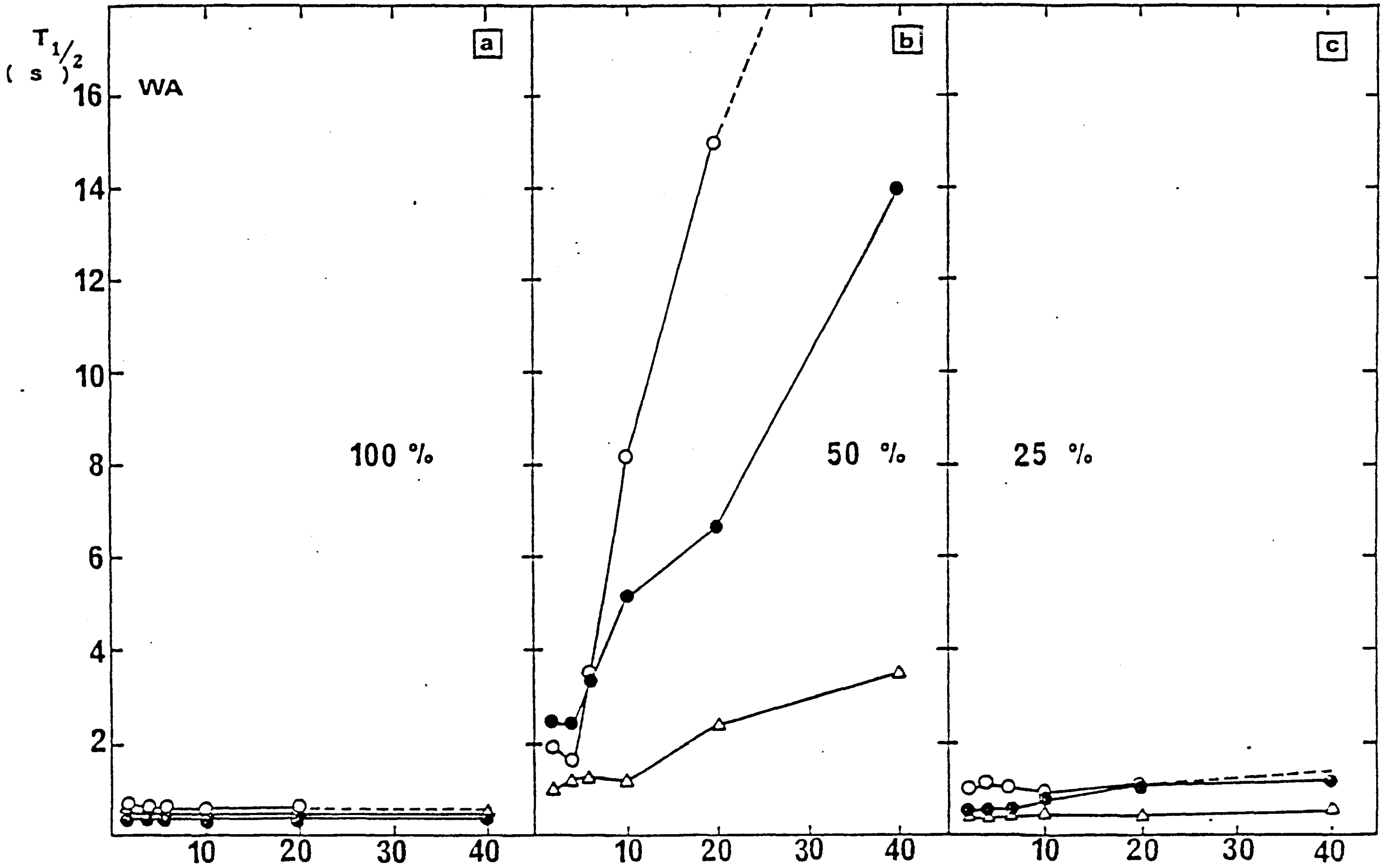

FIG. 3 – 22 . Magnification discrimination for triangles. The sizes of the target are marked on each plot. The reference elements were of size 60% and 40% (○), 60% (△) and 40% (●). Least square regression coefficients for the 50% target with the mixed reference field was 0.784±0.0602.

This is because the targets here are either much larger or much smaller than both the reference elements used. For the 50% target the discrimination is non-parallel for the mixed and for each of the simple reference fields, although values are greater for the mixed reference field.

In order to demonstrate clearly the finding that processing can be parallel for the simple reference fields and non-parallel for the complex fields, further sets of measurements were made. In this case the two classes of reference elements were of linear size 100% and 30%, whilst the target sizes were 83%, 62% and 45%, The results are illustrated in Fig 3-23, plotted for each target separately. $T_{\frac{1}{2}}$ for target discrimination with the mixed reference elements increases for all the targets, i.e. non-parallel processing. For the fields composed of single reference element, the processing is parallel for all the targets, except in one condition, for the 83% target with 100% reference elements.

(iii) Squares:

Magnification discrimination was also examined for squares oriented vertically, with targets of relative size of 100%, 50% and 25%, (a sample field is illustrated in Fig 3-24, and the various combinations of reference elements in Fig 2-5).

Data for the reference elements with relative sizes of 80% and 31% is given in Fig 3-25 for two subjects, and data are plotted separately for each target size. $T_{\frac{1}{2}}$ values for the mixed reference fields are higher than values for those composed of a single reference element. Target discrimination is non-parallel for the

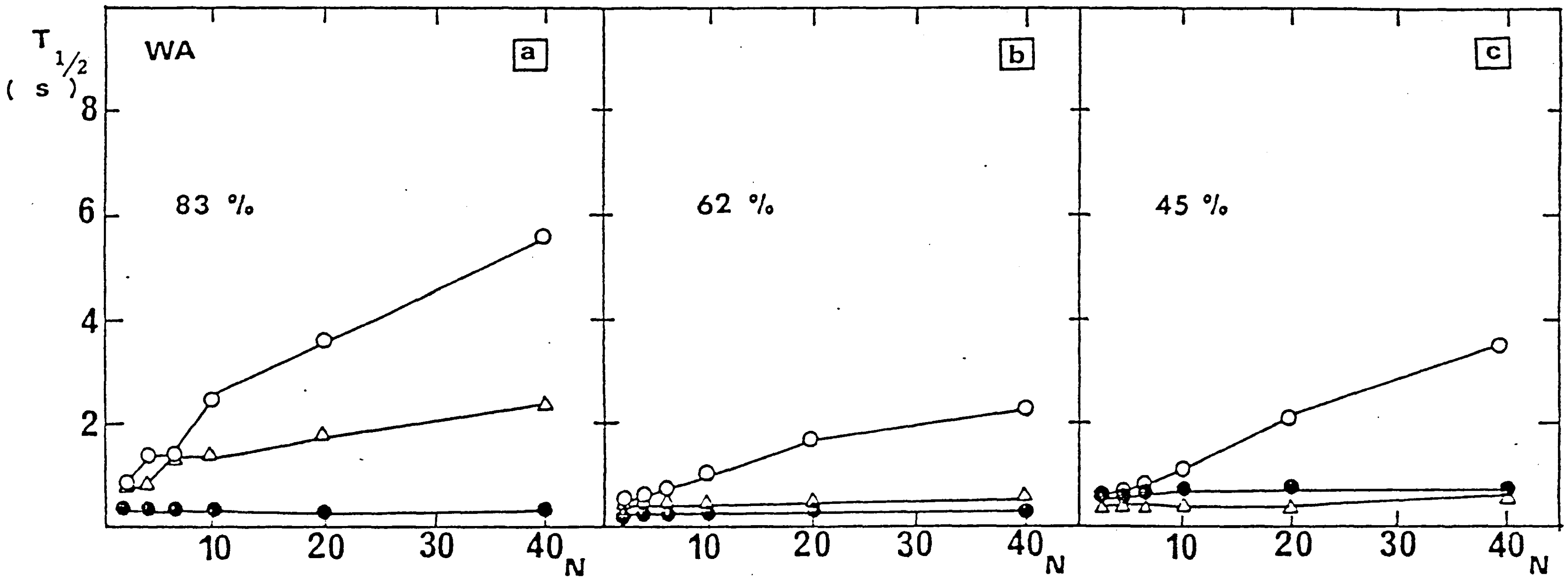

FIG. 3 _ 23 . Magnification discrimination for trianglular elements. The target size is marked on each plot. The reference elements were of size 100% and 33% (O), 100% (Δ) and 30% (●). Least square regression coefficients for the mixed reference field for the 83% target is 0.122±0.0091, for the 62% target is 0.046±0.0039 and for the 45% target is 0.077±0.0030. Subject WA.

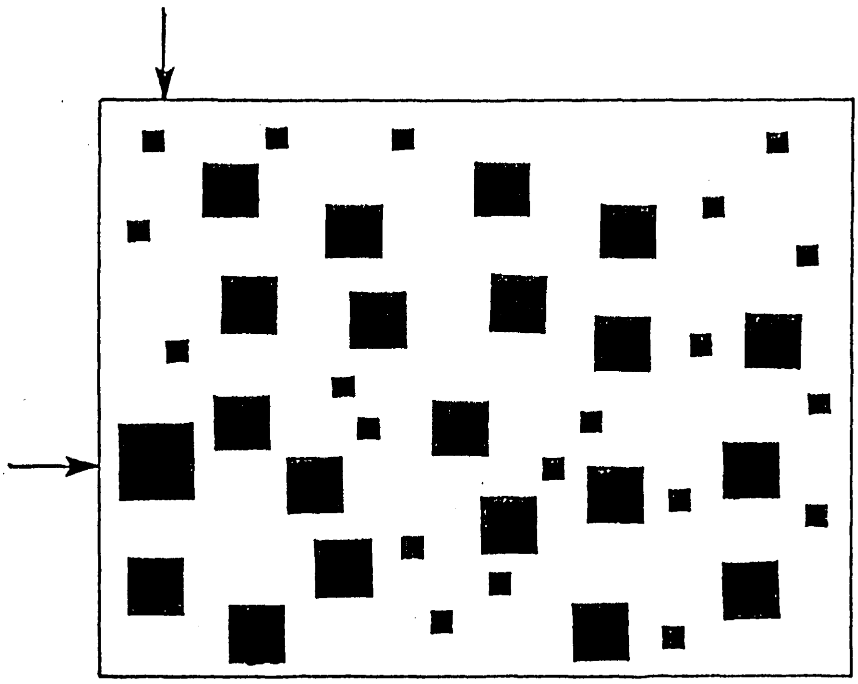

FIG. 3-24. An example of a stimulus consisting of two classes of square elements of two relative linear sizes, and a target of a different size, used for magnification discrimination measurements.

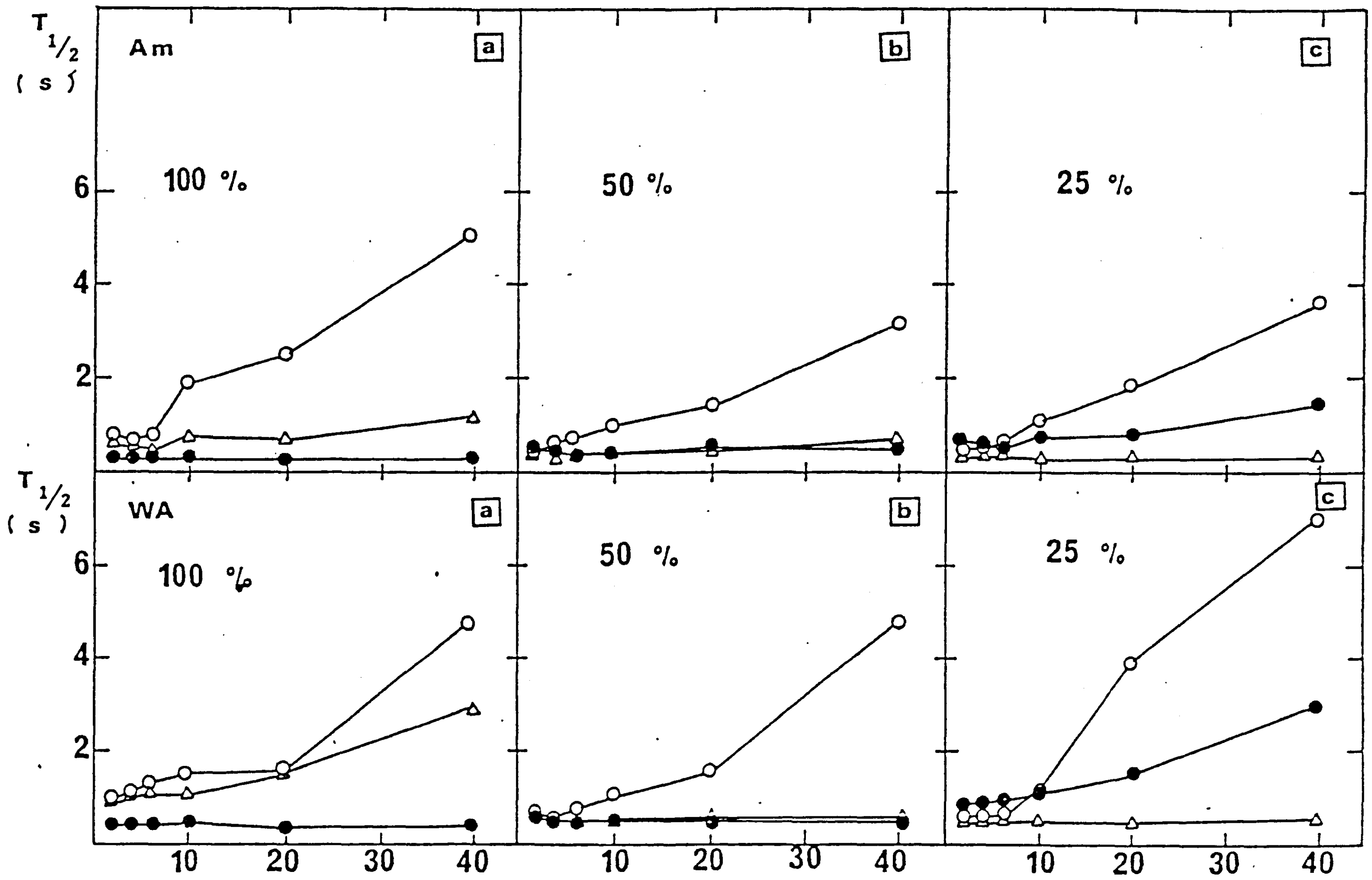

FIG. 3-25. Magnification discrimination for square elements. Results for two subjects. The target size is noted on each plot. The reference elements were of linear size 80% and 31% (O), 80% (Δ) and 31% (●). Least square regression coefficients with the mixed reference field, subject WA were: for the 100% target 0.095±0.0163; for the 50% target 0.108±0.0141; and for the 25% target 0.180±0.0133; for subject AM, for the 100% target 0.117±0.0079; for the 50% target 0.071±0.0042 and for the 25% target 0.085±0.0019.

mixed reference fields, as well as for one or other of the simple fields, except for the 50% target where it is parallel for the simple reference fields. Thus for the 50% target there is a clear transition from parallel processing for the simple reference fields to serial or non-parallel processing for the mixed reference fields. Similar results were obtained by two other subjects, and in Fig 3-26, their data are presented for targets with the mixed reference elements. Data are given in Fig 3-27 for 72% and 35% reference elements and are plotted separately for each target. In this case it should be noted that the 100% target is discriminated in parallel with the simple reference fields, and with the mixed reference field. The 50% target shows a clear transition from parallel to non-parallel in changing from the simple to the mixed reference fields. For the 25% target, discrimination was non-parallel for the mixed reference field but the difference between the data for the simple and mixed reference fields is less marked in this case. Similar results were obtained for two other subjects, and their data are presented in Fig 3-28, for targets with the mixed reference elements.

The next set of data, given in Fig 3-29, refers to reference elements of relative sizes 60% and 33%. The results show that for the 100% targets $T_{\frac{1}{2}}$ is completely independent of the number of reference elements, no matter if the reference fields are made up of single or mixed elements. For the 50% and 25% targets, $T_{\frac{1}{2}}$ is dependent on the number of elements for the mixed reference field and also for one or the other of the simple fields. Similar results are given in Fig 3-30 for two subjects with data presented for the mixed reference field only.

The last set of data obtained with the square elements

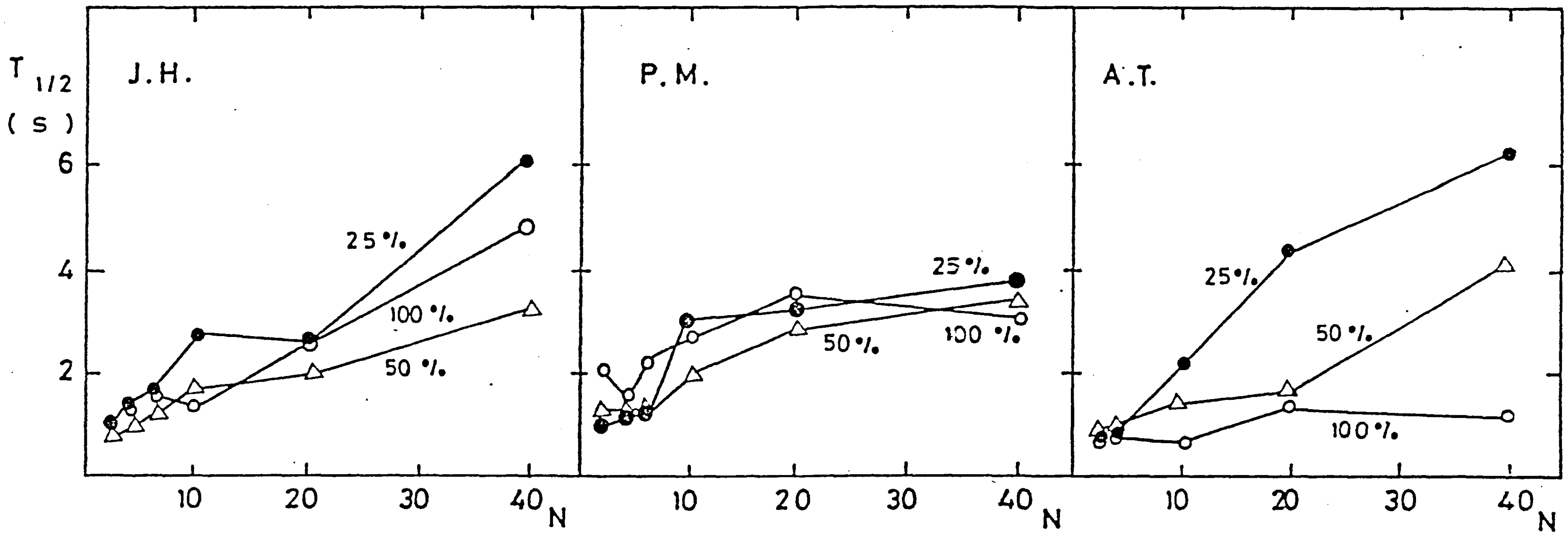

FIG. 3-26. Magnification discrimination with square elements. The reference field consisted of a mixture of two classes of elements, of size 80% and 31%, and the target size is noted with each set of data. Results for subjects JH and PM are similar to those of subject AT.

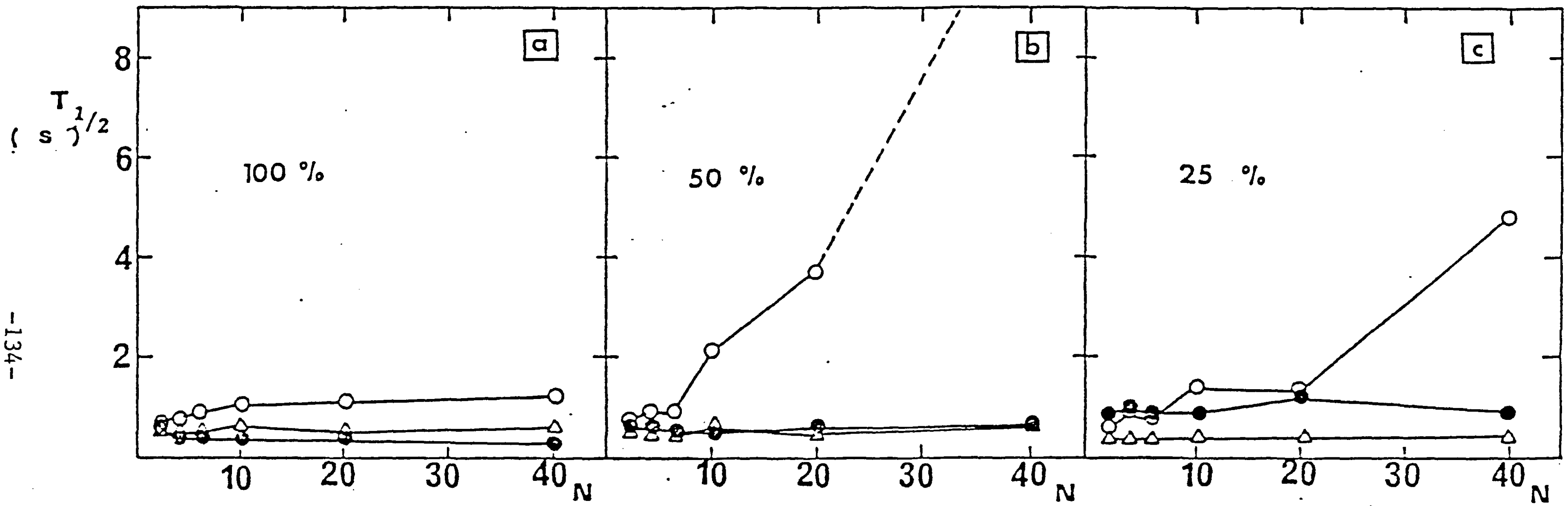

FIG. 3-27. Magnification discrimination for square elements with the target size labelled on each plot. The reference fields are; 72% and 35% (○), 72% (△) and 35% (●). Least regression coefficients for the mixed reference fields were for 100% target slope is 0.0088±0.0018, for the 50% target 0.295±0.0314, and for the 25% target 0.105±0.0178.

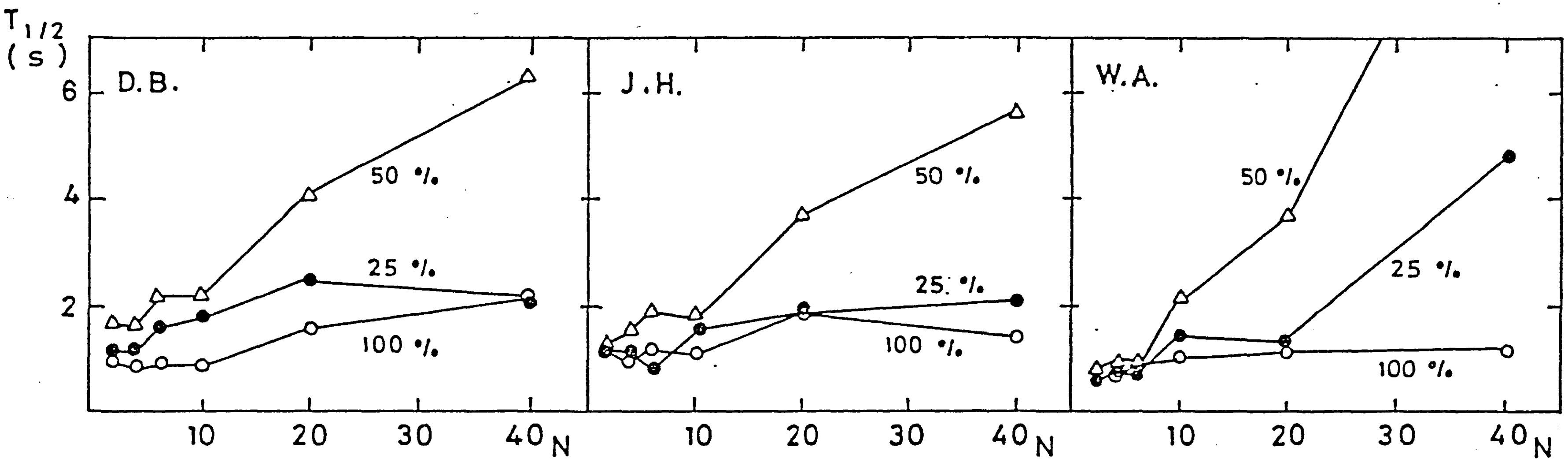

FIG. 3-28. Magnification discrimination with square elements. The reference field consisted of two classes of elements of linear relative size 72% and 35% and the target size is noted with each data set. Results are for DB and JH. They are similar to those of WA.

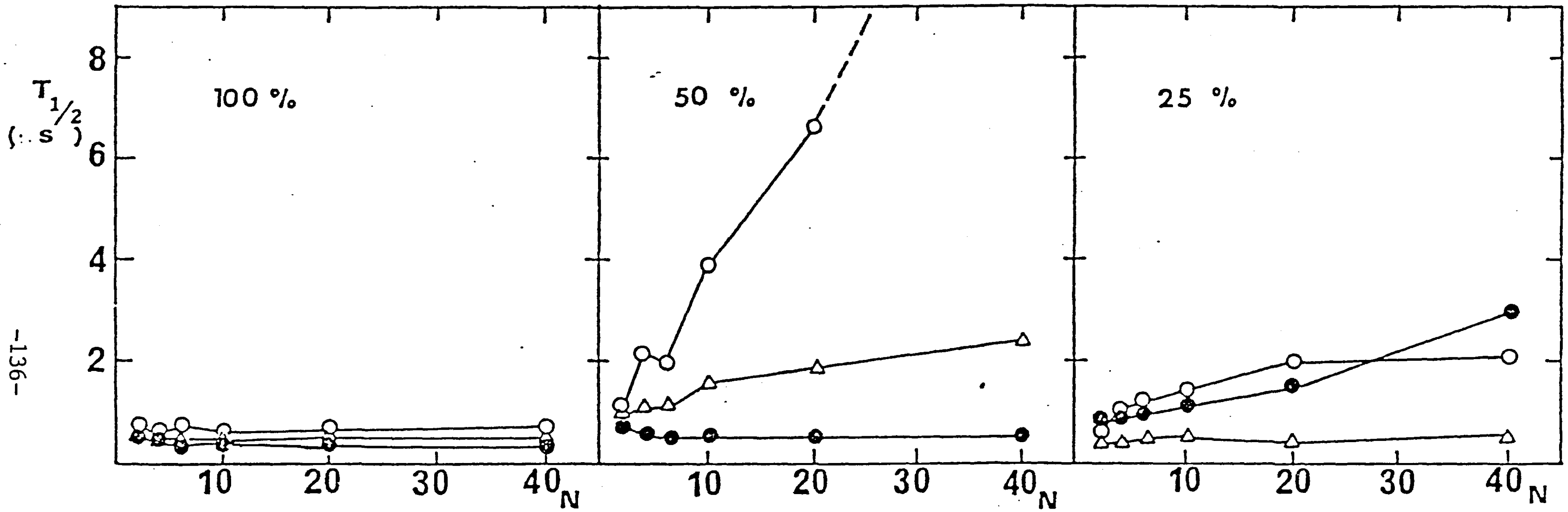

FIG. 3-29. Magnification discrimination for triangular elements with the target size given on each plot. The reference elements were of linear size 60% and 33% (○), 60% (△) and 33% (●). Least squre regression coefficients for the mixed reference fields were; for 50% target is 0.304±0.0207 and for the 25% target 0.033±0.0081. Subject WA.

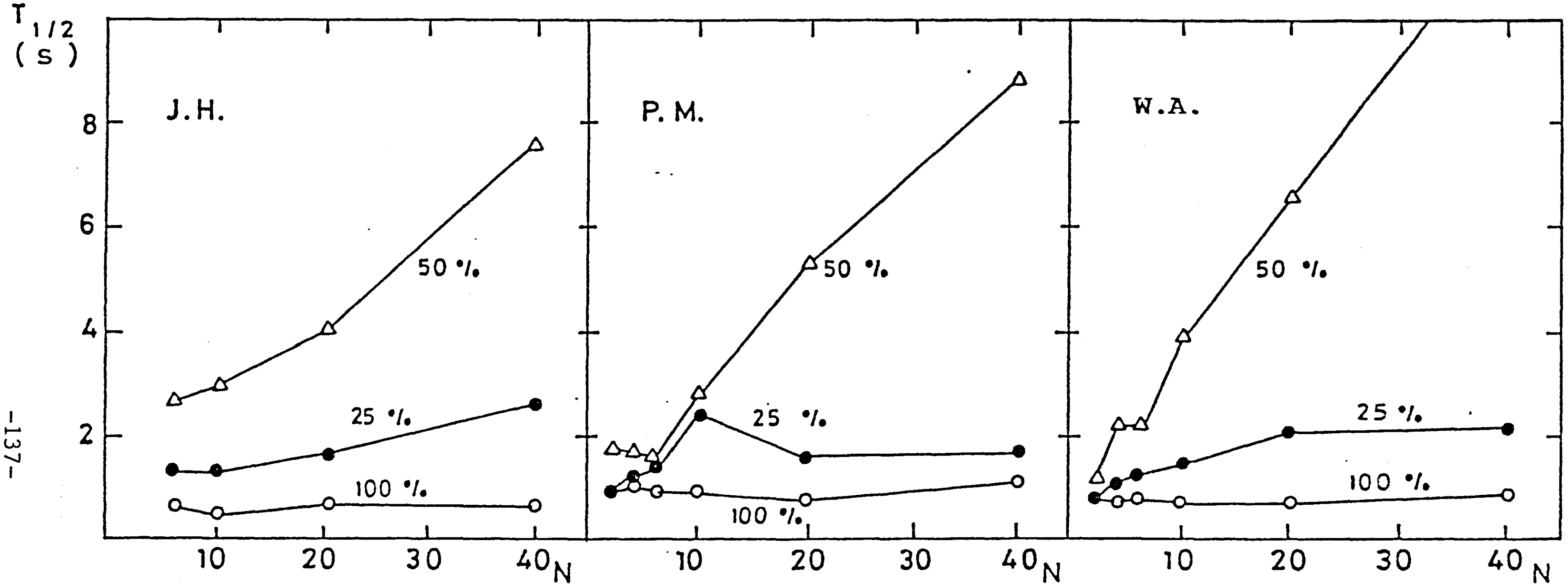

FIG. 3-30. Magnification discrimination with square elements. The reference fields consisted of a mixture of two classes of elements of relative linear size 60% and 35%. The target size is marked with each set of data. Results shown for subjects JH and PM, which are similar to those for subject WA.

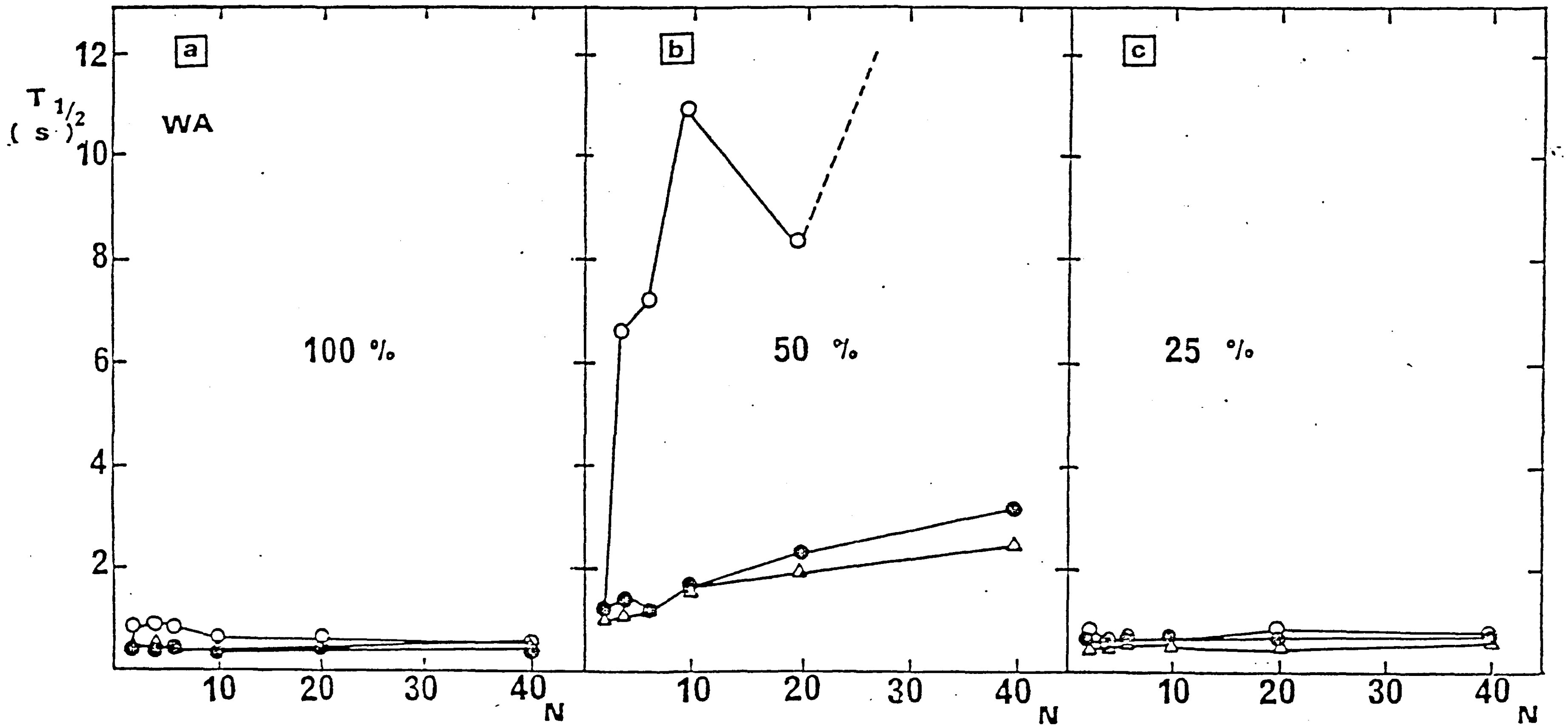

FIG. 3-31. Magnification discrimination for square elements. Each plot is for a target size as marked. Reference elements were of size; 60% and 42% (O), 60% (Δ) and 42% (●). Least square regression coefficients for the 50% target with the mixed reference field has a value of 0.261±0.0318. Subject WA.

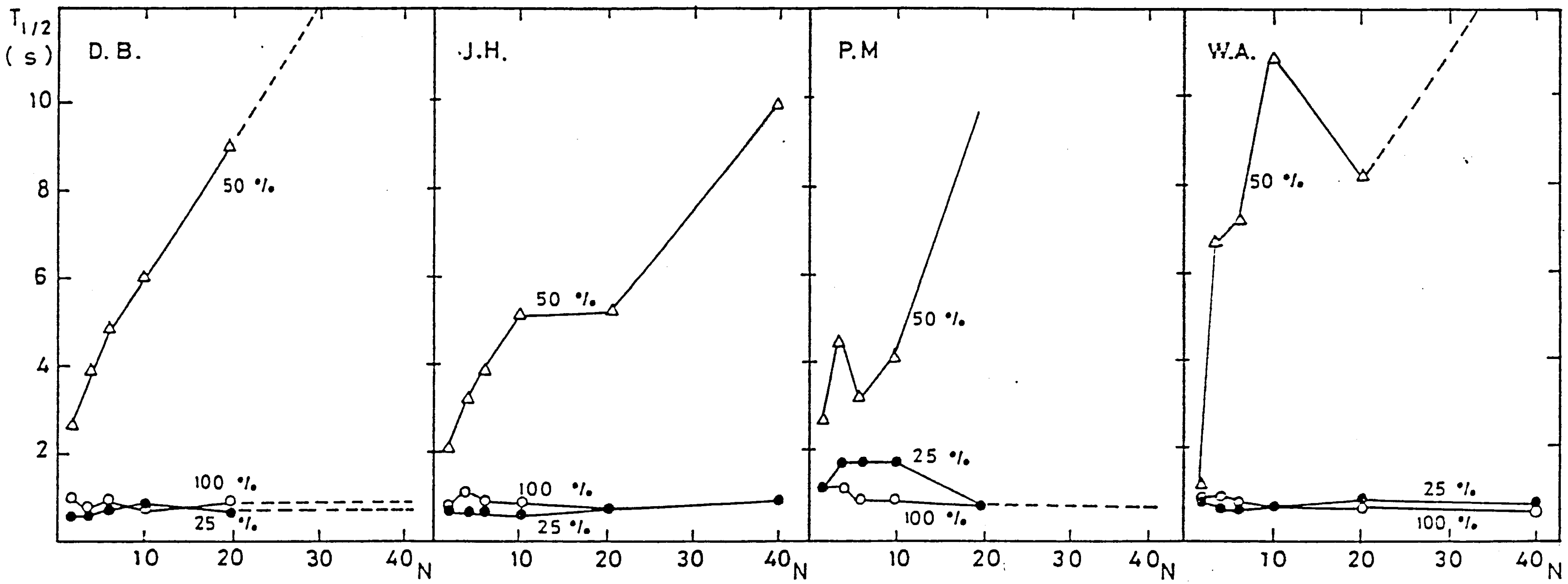

FIG. 3-32. Magnification discrimination with square elements. The reference fields consisted of two elements of relative size 60% and 42% and the target size is marked with each set of data. Results are given for subjects DB, JH and PM and are similar to those obtained for subject WA.

is for reference sizes of 60% and 42%. The results are given in Fig 3-31 and show that $T_{1/2}$ values for both the 100% and 25% targets are not dependent on the number of elements in the reference field, for either the mixed or the simple reference fields. For the 50% target, however, $T_{1/2}$ increases markedly with increase in the number of reference elements, both for the simple and complex reference fields. Similar results were obtained for three other subjects, and their data for the mixed reference field only are presented in Fig 3-32.

3.5. Discussion:

In this chapter, I have described the effects on discrimination of a single target of introducing a second class of element into the reference field. The data establish that target discrimination is influenced greatly by the complexity of the reference field. The experimental results for discrimination of target orientation and magnification can be divided into three groups:

1. For the first group of results, $T_{1/2}$ values for discrimination of the target is independent of the number of reference elements, N, for both the simple reference fields and for the mixed reference fields, that is, parallel discrimination of the target, as described by Javadnia and Ruddock (1988a), can be performed even with the mixed fields, (e.g. Fig 3-2, 3-3, 3-19a, 3-22a&c, 3-27a, 3-29a, 3-31a&c). This occurs only when the target orientation angle or its magnification lies well outside the range encompassed by the two components of the mixed reference fields.

2. For the second group of results, $T_{1/2}$ values for

detection of the target is parallel for the simple reference fields, but is serial for the mixed reference fields. In this group the transition from parallel processing to non-parallel processing caused by introduction of the mixed reference field is clear, (e.g. Figs 3-4, 3-5, 3-12, 3.14, 3-21b, 3.23b&c, 3-25b, 3-27b&c).

3. The third group of results shows that the $T_{\frac{1}{2}}$ values are greater for the mixed reference field than for the single reference fields, (e.g. Figs 3-6, 3-7a, 3-8, 3-9, 3-10, 3-18, 3-19b&c, 3-21a&c, 3-22b, 3-23a, 3-25a&c, 3-29b&c, 3-31b), but processing is non-parallel for at least one of the simple reference fields, as well as for the complex field.

The results of these experiments, summarized above, are consistent with common sense expectations of visual performance, but the observation that a mixture of two elements in the reference field can prevent parallel processing, despite the fact that such processing is possible when either is used alone, requires some consideration. Javadnia and Ruddock (1988a) have shown that orientation discrimination is parallel (i.e. $T_{\frac{1}{2}}$ independent of N) for targets of greater than 5 deg. orientation from the reference elements. In these experiments, the targets were always rotated through an angle greater than 5 deg. relative to either class of reference elements. In the case of line orientation discrimination for reference fields composed of one component (Figs 3-2, 3-3, 3-4 and 3-5), target detection is always parallel, whereas with the mixture of two classes of reference elements with angular separation 40 deg. to 60 deg., $T_{\frac{1}{2}}$ is serial (i.e. $T_{\frac{1}{2}}$

varies with N; Figs 3-4 and 3-5). This suggests that the orientation bandwidth of the mechanism which mediates detection of the target is about ±25 deg. Psychophysical studies by grating adaptation methods of the orientation selectivity of central mechanisms sensitive to orientation and size (Blakemore and Campbell, 1969, Maudarbocus and Ruddock, 1973) and electrophysiological studies on orientation sensitive neurones of the striate cortex (Hubel and Wiesel, 1968) compares reasonably well with these estimates. Burton and Ruddock (1978) also showed from consideration of 2-D adaptation, that the receptive field which mediates grating adaptation is of finite length with a 3:1 length to width parameters, and that this predicts on orientation tuning of half width 20 to 30 deg.

Much higher angular resolution is attained in the parallel processing for the simple reference fields, which occur at target orientations of greater than 5 deg. This may be achieved by averaging of responses from a number of broadly tuned orientation mechanisms over the length of the long elements used as the stimuli. We can regard the effects of the mixed reference field in the present experiments as providing a measure of the orientation tuning associated with the underlying mechanism responsible for mediating discrimination of line orientation.

Looking at the results obtained with fields consisting of triangles with different orientations, we found that when the target orientation varied about 6-8 degs. from the reference elements, its discrimination is non-parallel for the single as well as the mixed reference field, while the latter give much higher $T_{\frac{1}{2}}$ values (Figs 3-6 to 3-8), and these observations are in agreement with Javadnia and Ruddock (1988a). For orientation differences greater than 8 deg. discrimination is parallel for the reference fields consisting of a single class of reference element and non-parallel for the mixed reference field. Fig 3-12 shows such data for targets which differ in orientation from the reference elements by ≥15 deg. This is also shown with reference fields made up of squares of 0 deg. and 45 deg. orientations (Fig 3-14), for which the target is discriminated in parallel with the simple fields, for all target orientations (8,16 and 28 degs.) while it is serially discriminated with the mixed reference fields. The transition from parallel to non-parallel discrimination is very clear here (Fig 3-15) with introduction of the second reference element.

Thus the mechanisms considered in the discrimination of orientation with two dimensional elements also show coarse tuning, in that for both triangles and squares, parallel processing is lost for combinations of reference elements, each component of which produces parallel processing by itself. Whether or not this can be attributed to the accuracy with which orientation discrimination is obtained for the component lines of the elements is uncertain. The experiments with an agnosic subject, HJA, showed that he could perform orientation discrimination normally for single lines, but was grossly defective for two dimensional elements, such as triangles and squares (Bromley et al., 1986). It was concluded that the mechanisms of orientation discrimination for single lines are different from those for two dimensional elements. The association of lines to form two dimensional pattern is also likely to give rise to inhibition between different orientation mechanisms, as described by Blakemore and Tobin (1972).

Results obtained with magnification measurements for lines show that target discriminations are serial for the mixed reference fields, when the target size differs from the reference by less than 25% to 30%, while at this difference it is parallel for the simple reference fields, (Fig 3-18; Javadnia and Ruddock, 1988a). It is clear from Fig 3-19 that when the target size difference is greater than 30% the process of discrimination is parallel. Similar results are obtained with triangles. The discrimination of the target is serial for the mixed reference elements when the magnification differences are less than 30%, while it is parallel for differences greater than that, (Figs 3-21, 3-22). When the target size falls within the range of the two reference elements the discrimination is serial even with differences in magnification of some 32% (Fig 3-23).

The results obtained with square patterns give similar results. The discrimination is serial for magnification differences of about 20% or less. It is also serial for 30% difference in magnification when the target size falls within the sizes of the two reference elements, (Fig 3-25), while it is parallel when the target is greater than the large reference element by 30% or more, (Figs 3-27, 3-29, 3-31).

As with orientation discrimination, the mechanisms for magnification discrimination show much coarser tuning when assessed by mixed reference fields than with a single class of reference element. This will be utilized in the experiments to be described in the following chapters.

CHAPTER FOUR

Chapter Four

Discrimination with Changes in Colour Luminance and Contrast

4.1. Introduction:

The visual system does not respond only to objects with spatial patterns of variable complexity, it also responds to the colour, luminance and contrast of these objects. Scenes around us, in every day life, are a mixture of coloured patterns with different luminances and varying contrast levels, and the visual system assesses all these factors in fixating objects in the field of view.

In Chapter Three, it was demonstrated that discrimination performance is dependent on the complexity of the reference field from which the target must be differentiated. In this Chapter, the parameters examined will be extended to include colour, luminance and contrast, in order to investigate their effects. The objective was to find out if the mechanisms responsible for discrimination of orientation and magnification are selective in response to colour, luminance and contrast polarity. In order to achieve this, the principle of using a mixture of two classes of reference elements was extended. Thus in addition to being differentiated by orientation or magnification, the two classes also differ in either colour, or luminance or contrast polarity. The aim was to examine whether, by introducing the additional differences between the classes of reference elements, they could still interact in determining discrimination performance.

4.2. Stimulus Patterns:

The stimulus patterns used in this Chapter are spatially very similar to those examined in Chapter Three, but with the additional parametric variations mentioned in the previous section. These are as follows:

1. For colour discrimination measurements, the two classes of reference elements used to construct mixed reference fields each had a different colour (Figs 2-6 and 2-7), and in most of the experiments, the two types of elements were matched in relative luminance whilst the targets had the same colour and relative luminance as one of the classes of reference element. The background (screen) colour was in some experiments black, whilst in others it was white or yellow. The colour and relative luminances for the reference elements, targets and screen are specified for each experiment. The combination of colours chosen for the reference elements formed the opponent pairs of red and green, and yellow and blue (Jameson and Hurvich, 1955). So for these experiments, the two classes of reference elements differed in colour, and they also differed in magnification or orientation for measurements of magnification and orientation discrimination respectively.

2. For experiments on contrast, the two classes of reference elements differed in contrast polarity relative to a background of intermediate luminance, all elements having the same chromaticity. The positive and negative contrast levels were of equal amplitude. The two classes of

element also differed in orientation for measurement of orientation and in magnification for measurements of magnification discrimination.

4.3. Subjects:

All the subjects who participated in these experiments were postgraduates at Imperial College. They were all experienced observers and possessed 6/6 visual acuity or better. The subjects are W.A. (38 years, female), A.M. (21 years, male) and J.S. (22 years, female).

4.4. Experimental Procedure:

As in Chapter Three, the subject was instructed to push one of two buttons, one for target seen and the other for no target present, as soon as a decision is made. The response time is logged by the computer and the value of $T_{\frac{1}{2}}$ was measured. (See Chapter Two for more details).

4.5. Results:

The results in this Chapter will be presented by graphs of $T_{\frac{1}{2}}$ against the number of reference elements, N. They are divided into two sections:

1. Discrimination with colour differences.

2. Discrimination with difference in contrast polarity.

In each of these sections, the discrimination of the targets is based on its orientation or on its magnification relative to that of the reference elements.

4.5.1. <u>Discrimination with Colours:</u>

In this set of experiments the colours used for the reference elements were either green (G) and red (R) or blue (B) and yellow (Y). (See chromaticity chart Fig 2-7).

4.5.1.A. <u>Orientation Measurements:</u>

(i) <u>Data with Variable Luminance in One of Two Classes of Reference Elements, which Also Differ in Colour:</u>

Preliminary experiments were performed in which the importance of the relative luminance of the differently coloured reference element was examined.

In these experiments, two classes of reference elements were used, and these differed both in colour and in relative luminance. $T_{\frac{1}{2}}$ was measured as a function of N, the number of reference elements, and as always in these experiments, equal numbers of the two classes of reference element were used in each case.

Some measurements are presented in Fig 4-1 and in detail in Appendix I, in which data are given for three target orientations, and for each combination of reference elements. The results show that the values of $T_{\frac{1}{2}}$ are similar for all the different combinations of reference element, and in order to make this point clear, the results have been replotted in Figs 4-2, 4-3 and 4-4. Here, values are given separately for each of the three target orientations, (6°,12° and 18°) and $T_{\frac{1}{2}}$

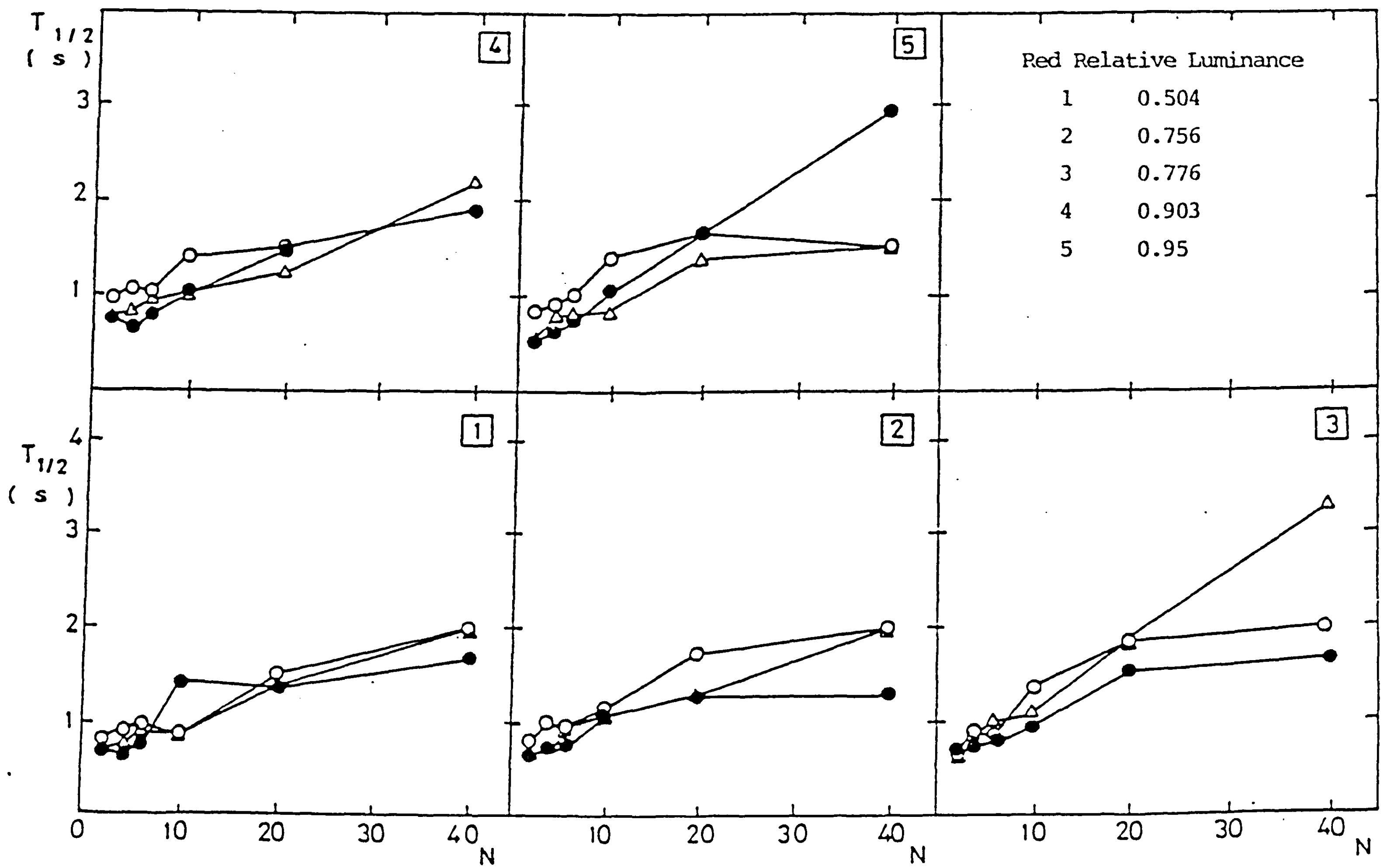

FIG. 4-1. Orientation discrimination for triangles with reference elements which differ both in colour and luminance. Reference fields consisted of mixed elements of green and red triangles oriented at 0° and 30° respectively. The red triangles differed in luminance for each set of results obtained as $T_{1/2}$ aganist N, as noted at the top right. The reference elements and the target were of fixed relative luminance 1.0 and the target orientation was 8° (O) orientation, 12° (Δ) and 18° (●).

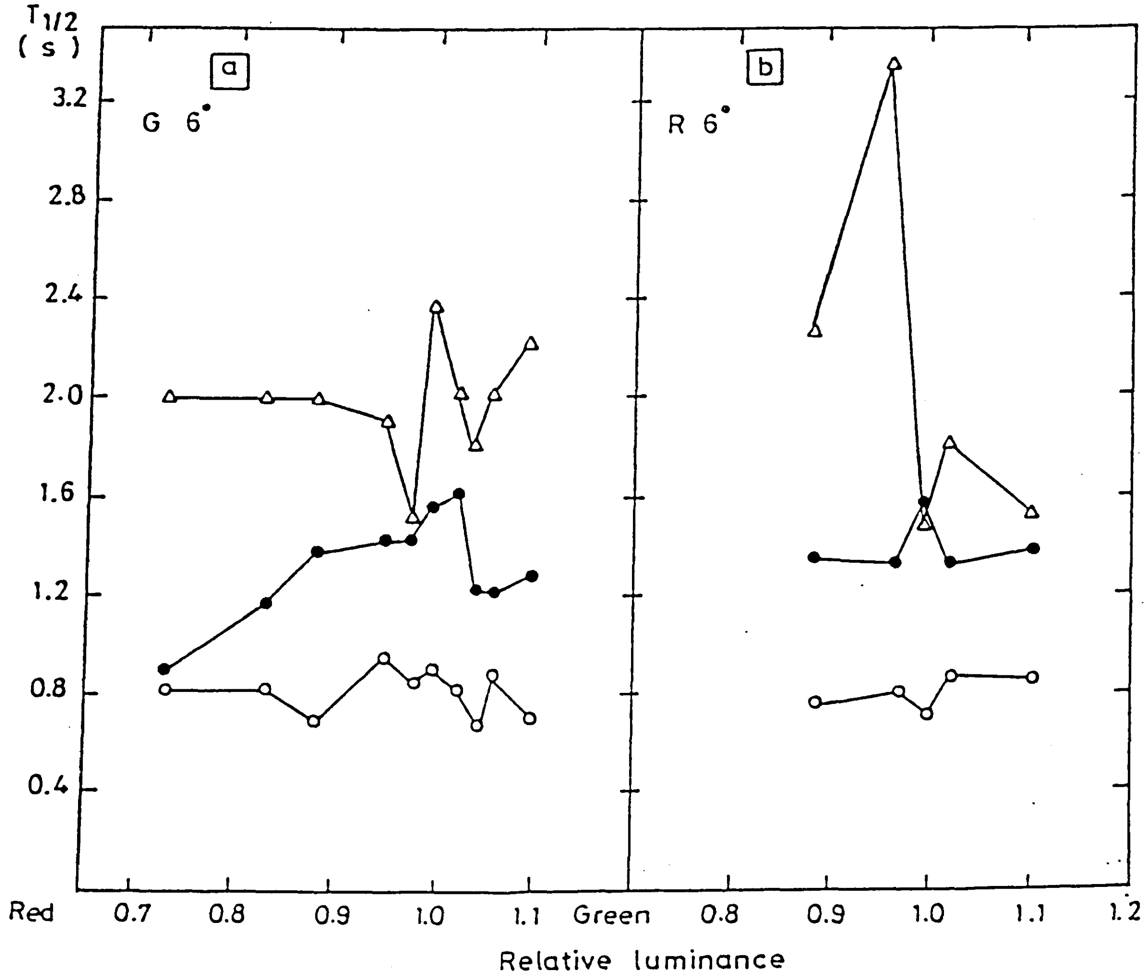

FIG. 4-2. Orientation discrimination for triangular elements with reference fields which differ both in colour and luminance, for a target orientation of 6°. Elements of fixed luminance were at a relative luminance of 1.0. (a) Reference fields are for mixed elements of green and red triangles, oriented at 0° and 30° respectively and a green target. The graph is for $T_{\frac{1}{2}}$ against the relative luminance of the red triangles. (b) Similar to a, but for red and green triangles oriented at 0° and 30° respectively, and a red target with the green triangle varying in relative luminance. (O) for N=2, (●) for N=10, (Δ) for N=40.

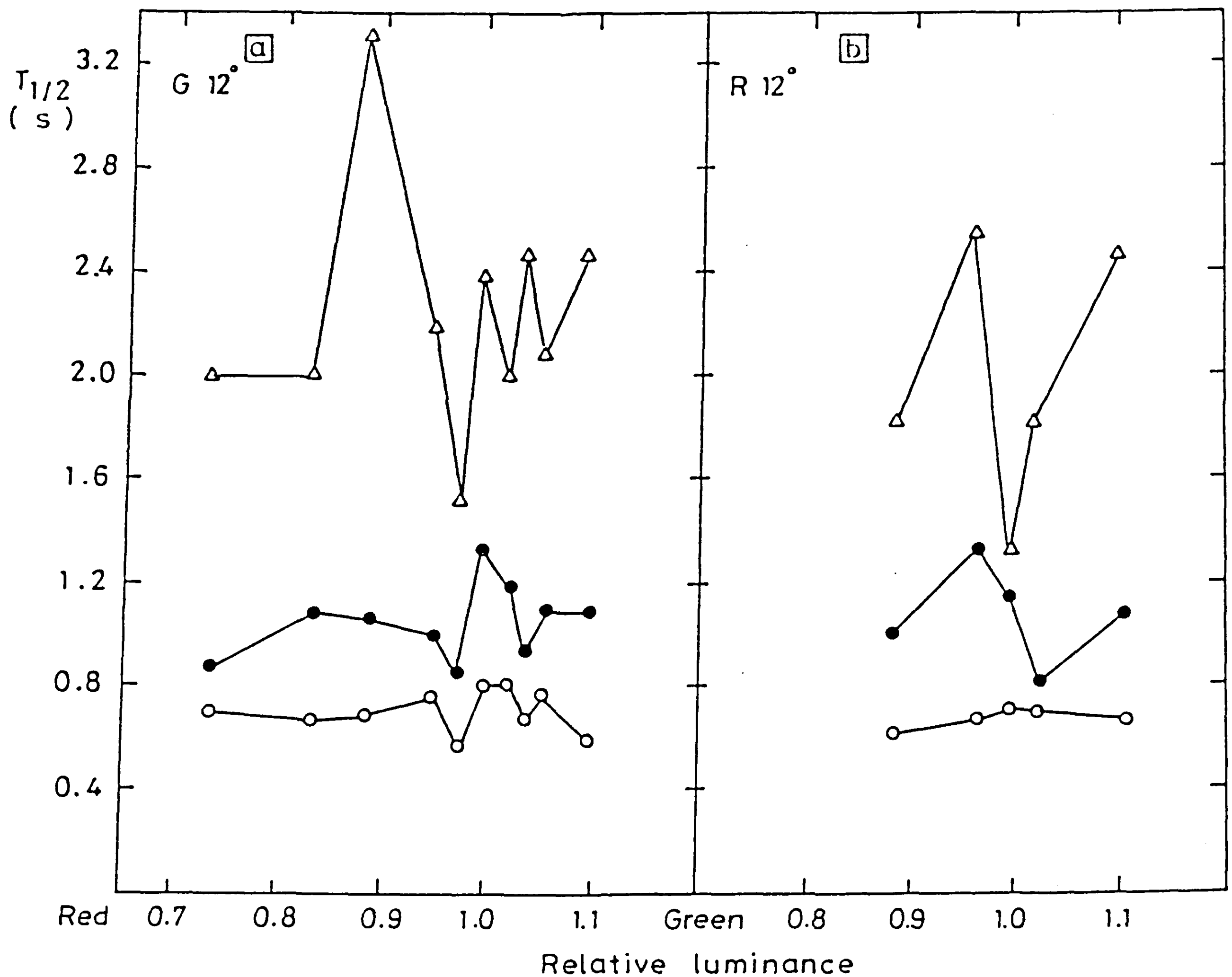

FIG. 4-3. Similar to Figure 4-2 but for a 12° target orientation.

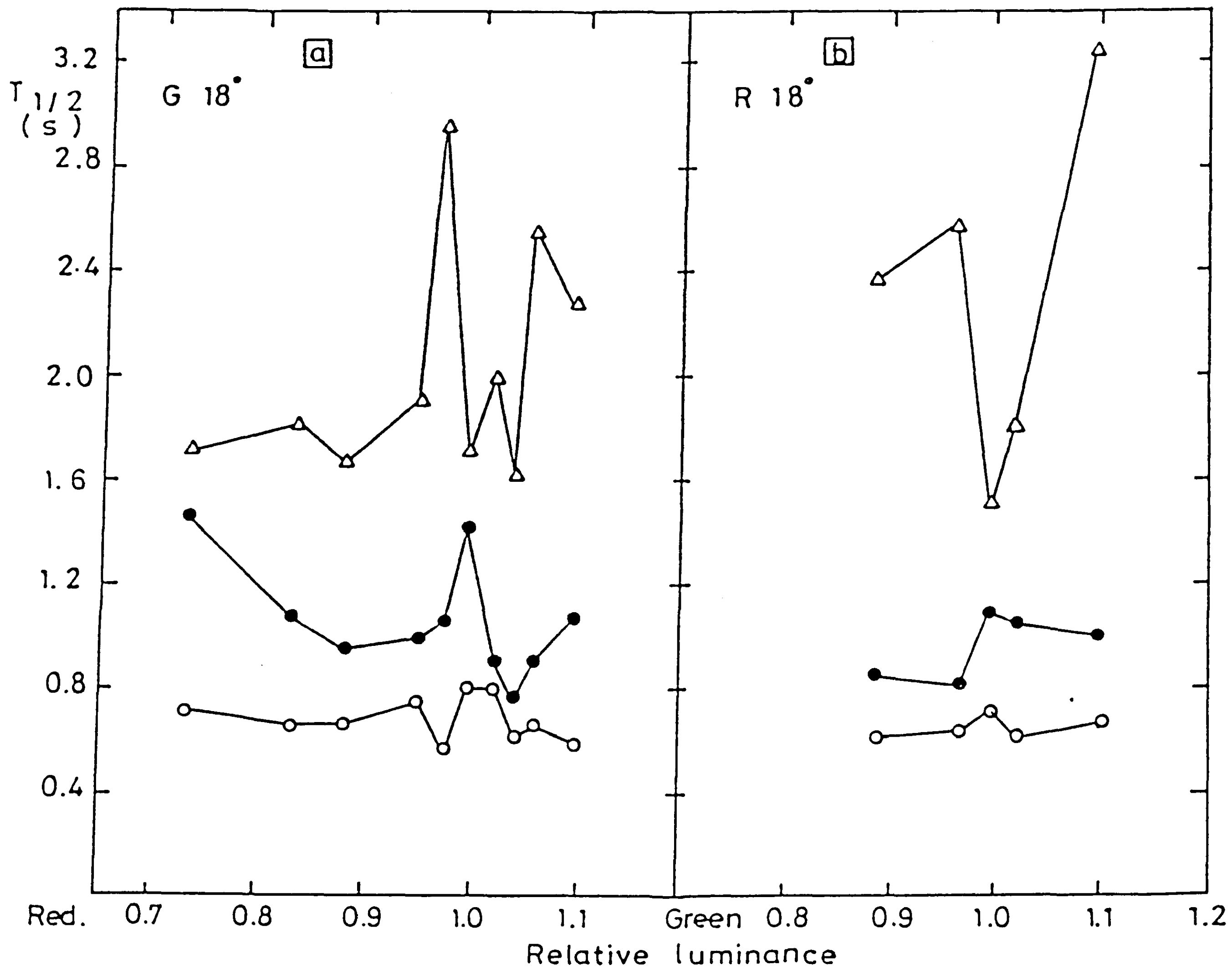

FIG. 4-4. Similar to Figure 4-2, but for an 18° target orientation.

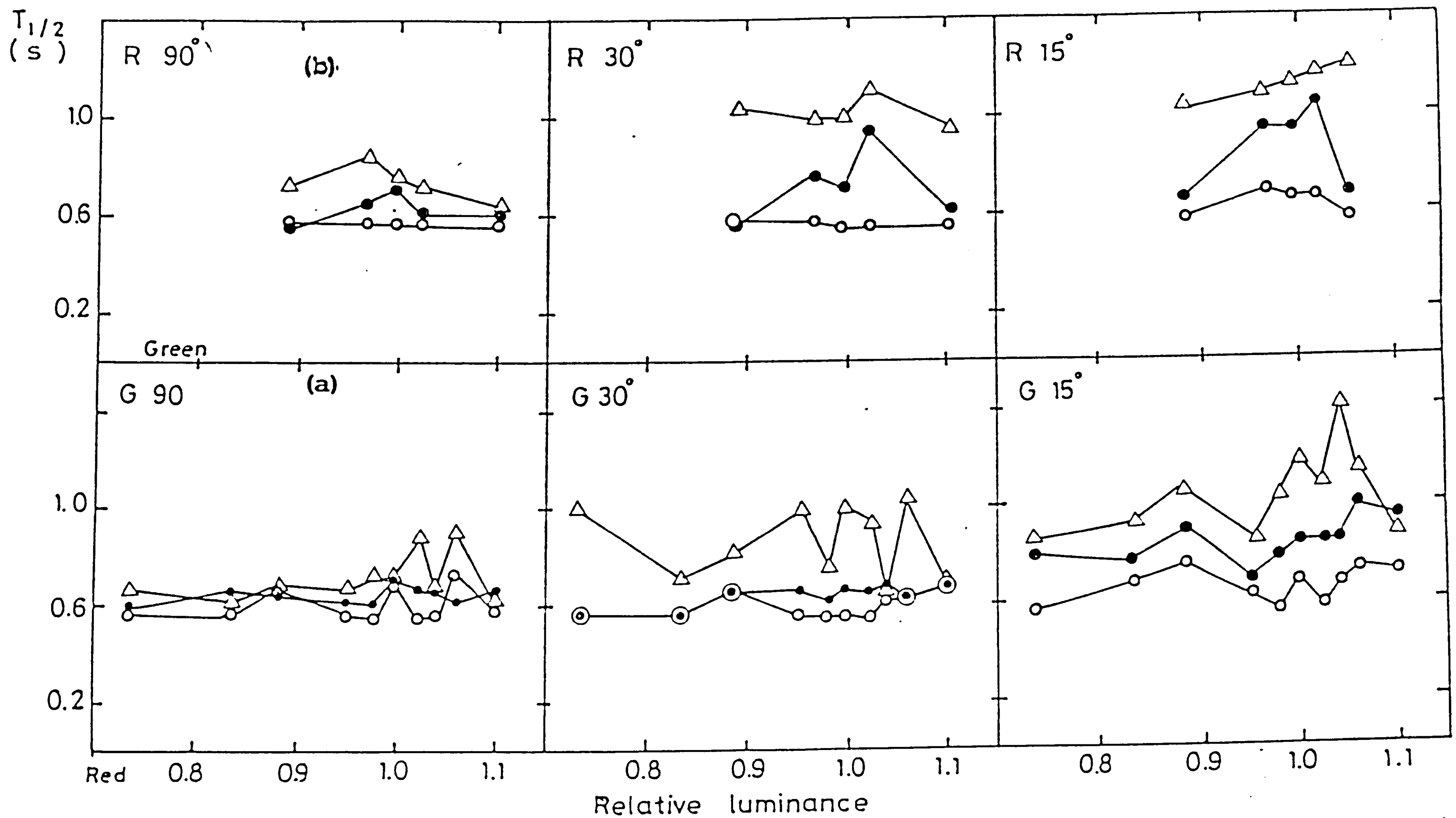

FIG. 4-5. Orientation discrimination for triangles with reference elements which differ both in colour and luminance. (a) Reference fields are for mixed elements of ▲ green and ▼ red with target orientation marked on each plot. (b) As for a, but for ▲ red and ▶ green reference fields. Data for (O) N=2, (●) N=10 and (Δ) N=40.

is plotted against the relative luminance, L, of the variable reference element. Each set of data points refer to a single value of N and for clarity, only a selection of the full set of data have been plotted, for N=2, N=10 and N=40. The results show that variations of $T_{\frac{1}{2}}$ with L are in most cases small, and that in general, there is no marked increase in the values for points around the value L=1 at which the two differently coloured reference elements have the same luminance. Similar results were obtained with another set of target orientations (30°,90° and -15°, Fig 4-5). Thus, it is concluded that in measurements made with two classes of differently coloured reference elements, the relative luminance of the two element is not a critical factor, and any small error in setting them to equal luminance will not have a significant effect on the measured values of $T_{\frac{1}{2}}$. In the remaining experiments of this type, therefore, all measurements were made with two differently coloured classes of reference element set at , nominally, the same luminance.

(ii) <u>Orientation Discrimination with Triangular Elements:</u>

In order to assess the effect of colour differences, $T_{\frac{1}{2}}$ was measured as a function of N, and values are plotted for three conditions:

a) Where one class of reference is coloured differently to the other.

b) When both classes of reference element have the same colour.

c) When only one class of reference element is present.

For example the data of Fig 4-6 refer to one class of reference element, green, pointing upright, whilst the other, oriented at 30 deg., is coloured either red or green, or is absent. The targets were in every case green.

Comparing the $T_{\frac{1}{2}}$ values for the mixed reference fields, i.e. with both orientations of the reference elements, it is apparent that they are lower for the reference fields in which the two reference orientations differ in colour, (Fig 4-6, for two subjects). The $T_{\frac{1}{2}}$ values for the reference fields composed of the two colour components are, none the less, still greater than those for a simple reference field consisting of a single reference orientation. Thus the differently coloured reference elements cannot be entirely rejected in carrying out the discrimination measurements. It should also be noted that the size of the difference between the $T_{\frac{1}{2}}$ values for the two colour and single colour reference fields depend on the target orientation. When the orientation of the green target is close to that of the green reference element(i.e. 6 deg. orientation) there is little difference between the two sets of data, whereas when it is closer to that of the red reference element (18 deg. orientation) the differences are larger.

Similar effects are observed with the red and green elements reversed, i.e. upright red and green reference elements rotated through 30 deg., with red targets (Fig 4-7). They are also observed with different orientations of the reference and target elements (Fig 4-8) and for different colour combinations (Fig 4-9).

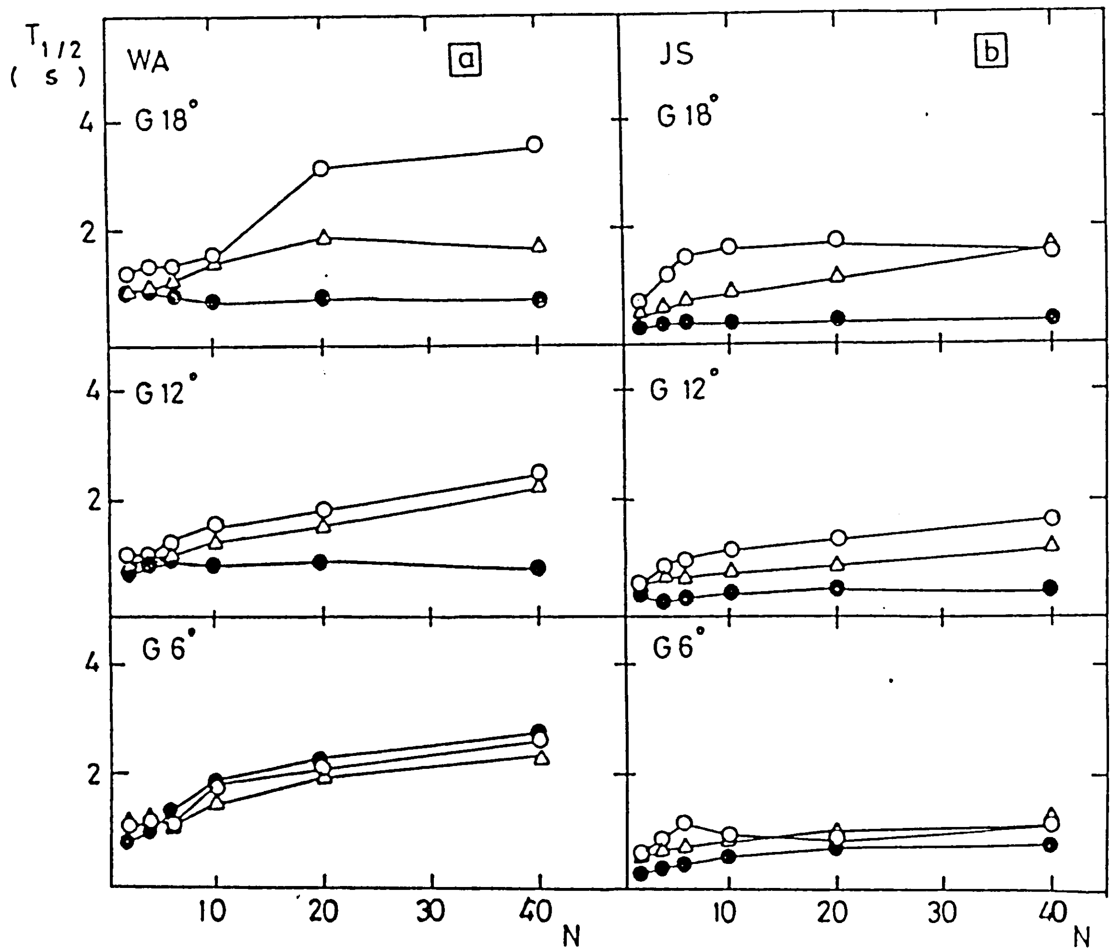

FIG. 4-6. Colour and orientation discrimination for green (G) and red (R) reference elements, matched in luminance, and green targets. Data for two subjects. Target orientation and colour are given on the upper left corner of each plot. The reference elements were ▲ and ◀, both green (○); ▲ green and ◀ red (△); ▲ green (●).

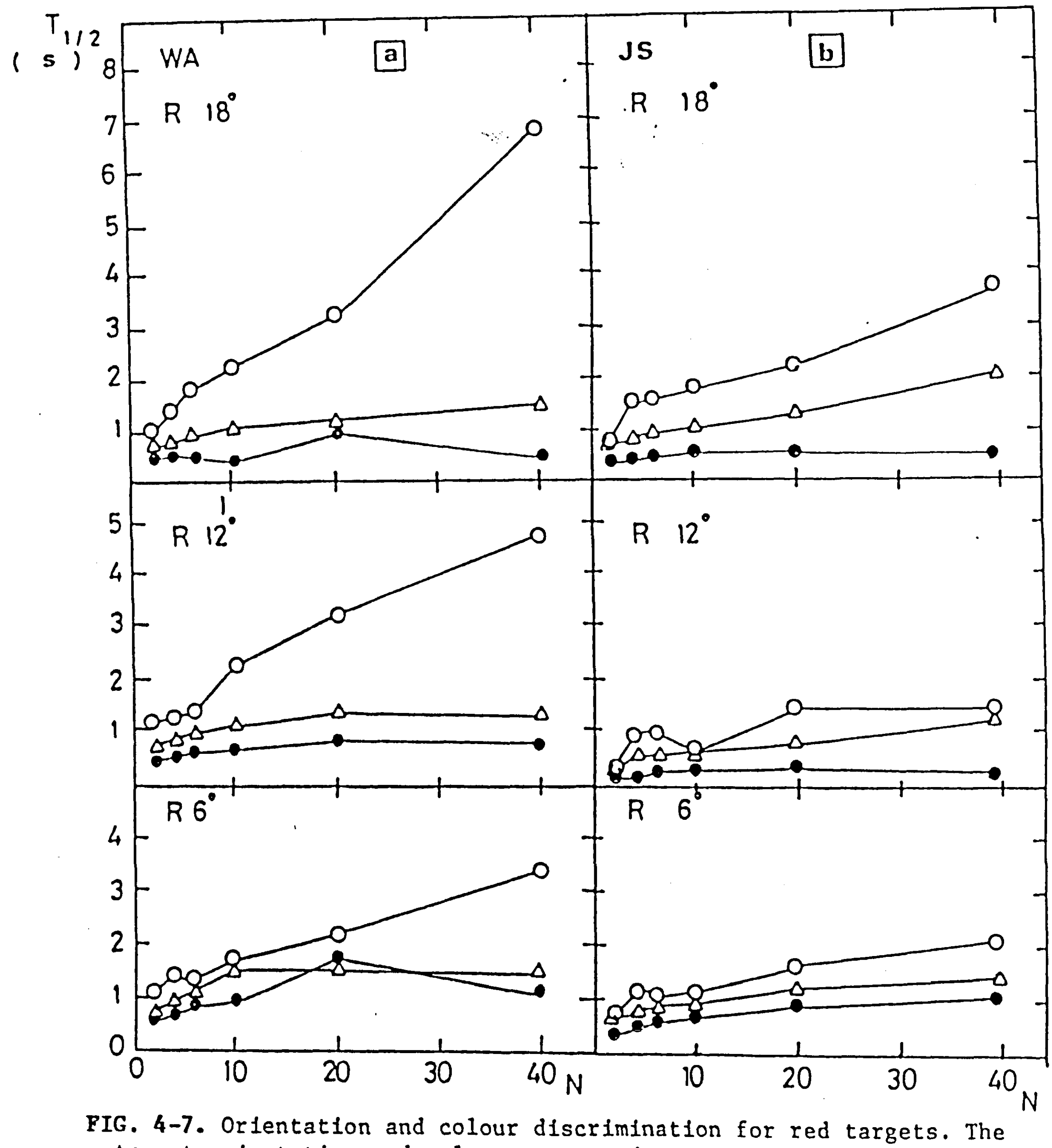

FIG. 4-7. Orientation and colour discrimination for red targets. The target orientation and colour are noted on each plot. The reference elements were ▲ and ◀ both red (○); ▲ red and ◀ green (△) and ▲ red (●). Results are for two subjects (a) for WA, (b) for JS.

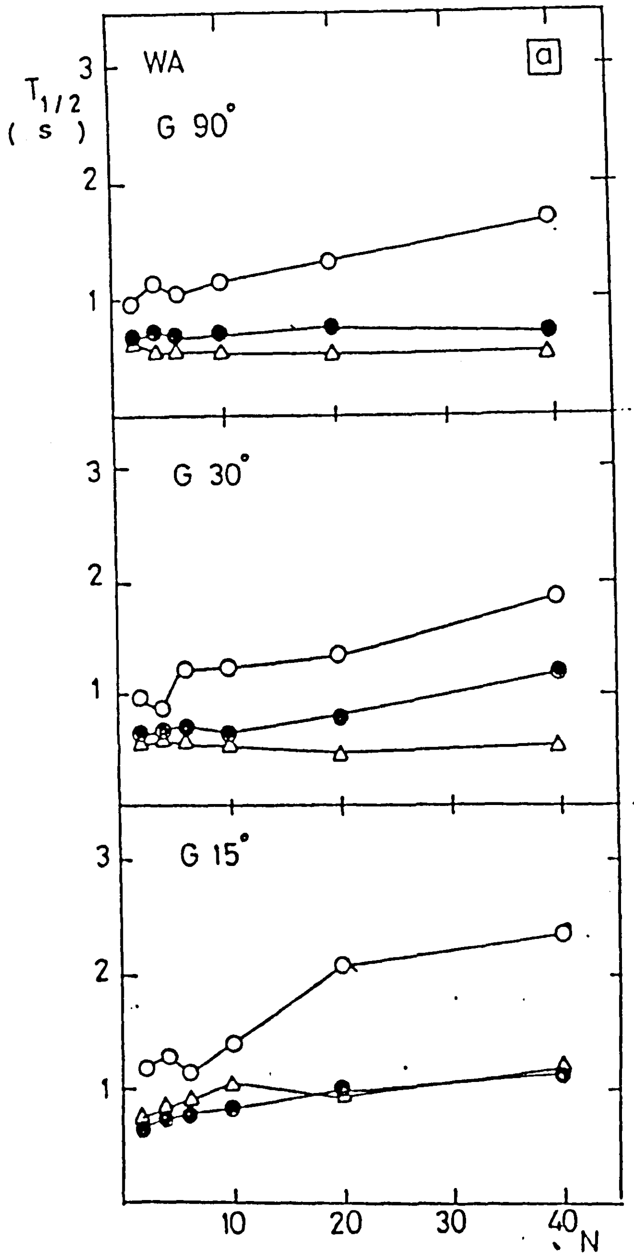

FIG. 4-8. Colour and orientation discrimination for triangles. Each plot is for the target orientation noted on the plot. The reference elements were ▲ and ▼ both green (O); ▲ green and ▼ red (●); ▲ green (△). The targets were green in each case.

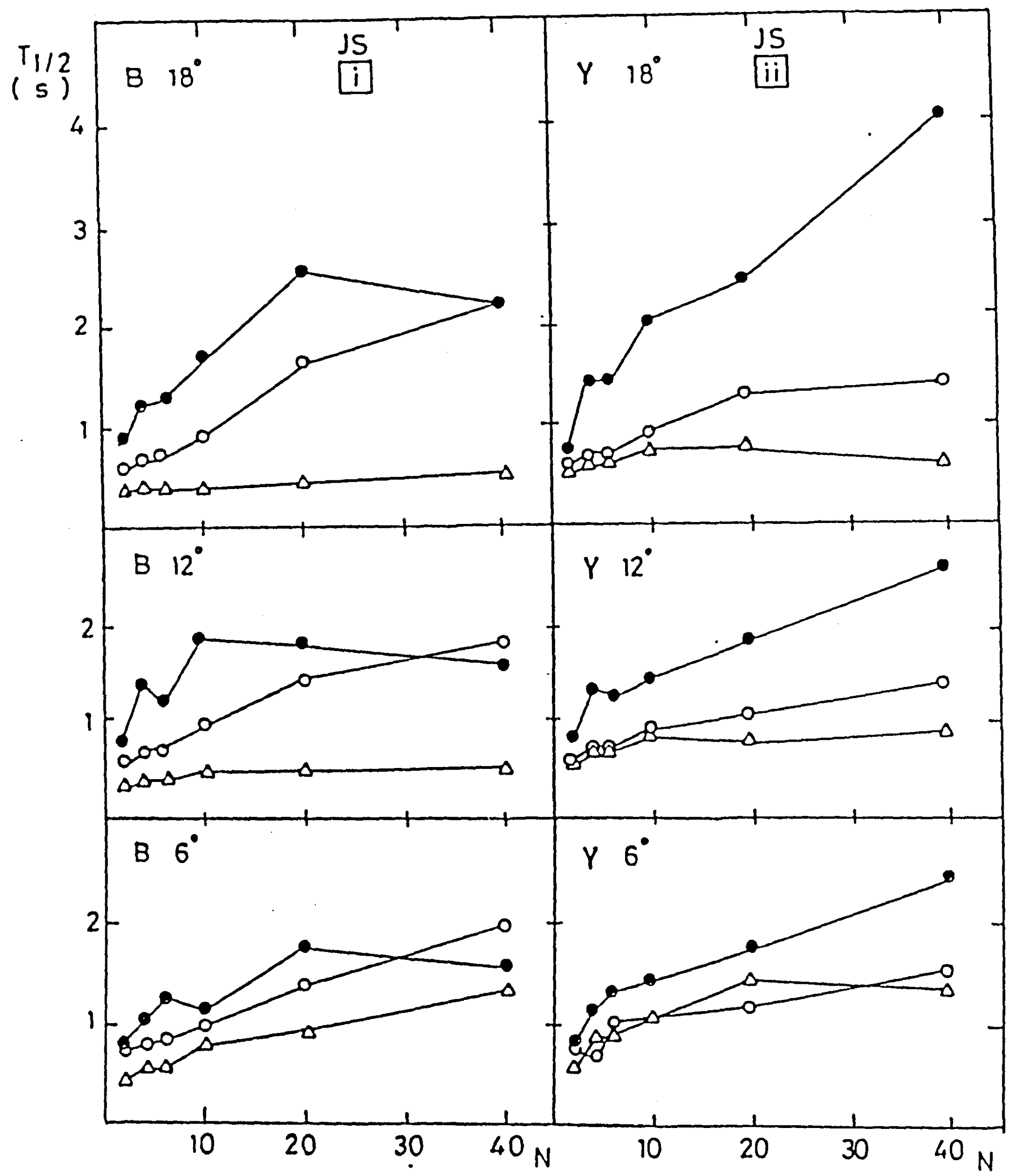

FIG. 4-9-b. Colour and orientation discrimination for triangles (i) for blue (B) targets with orientation specified on each plot, for reference elements ▲ and ◀ both blue (●); for ▲ blue and ◀ yellow (O) and ◀ blue (△). (ii) For yellow (Y) targets with orientation specified on each plot, tor reference elements ▲ and ◀ both yellow (●); for ▲ yellow and ◀ blue (O) and ▲ yellow (△).

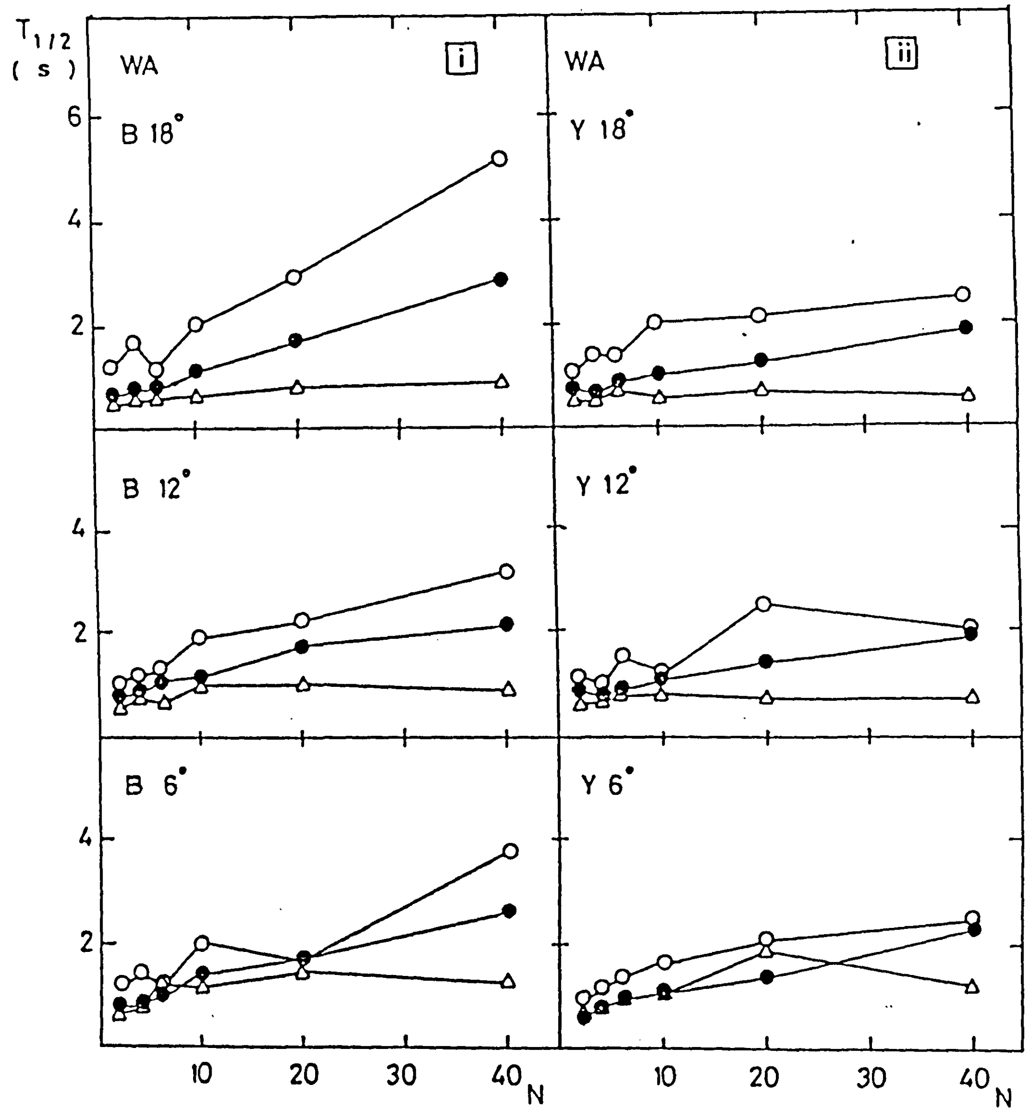

FIG. 4-9-a. Colour and orientation discrimination for triangles. (i) for blue (B) targets with the orientation specified on each plot with reference elements ▲ and ◀ both blue (O); ▲ blue and ◀ yellow (●) and ▲ blue (Δ). (ii) Similar measurements but for yellow (Y) targets with reference fields: ▲ and ◀ yellow (O); ▲ yellow and ◀ blue (●) and ▲ yellow (Δ).

(iii) <u>Orientation Discrimination with square Elements:</u>

Measurements similar to those described for triangular elements were also performed for square elements. The pairs of reference elements were oriented in an upright position and at 45 deg. rotation, and data for the case in which the former were always green and the latter either red or green with green targets, are given in Fig 4-10. In this case, the $T_{\frac{1}{2}}$ values for the mixed reference field which contained two colours are much less than those for fields which are of a single colour. Indeed, processing in the former case is almost always parallel, (i.e. $T_{\frac{1}{2}}$ independent of N). Further, the $T_{\frac{1}{2}}$ values for the mixed reference field composed of red and green elements differ little from those for the simple reference field consisting of only upright green elements, thus it seems that in this case, the red elements are almost completely neglected.

Very similar results were obtained with the roles of the red and green elements reversed, i.e. with the red reference elements oriented upright and the green reference elements at 45 deg., and with red targets. The results are very similar to those shown in Fig 4-10, as is clearly demonstrated in Fig 4-11, in which the data for the two types of mixed reference fields, with different colours, are plotted together, and are almost identical, (for two subjects).

Other data for a yellow-blue combination of colours are plotted in Fig 4-12 and the results are very similar to those obtained with the red-green combinations.

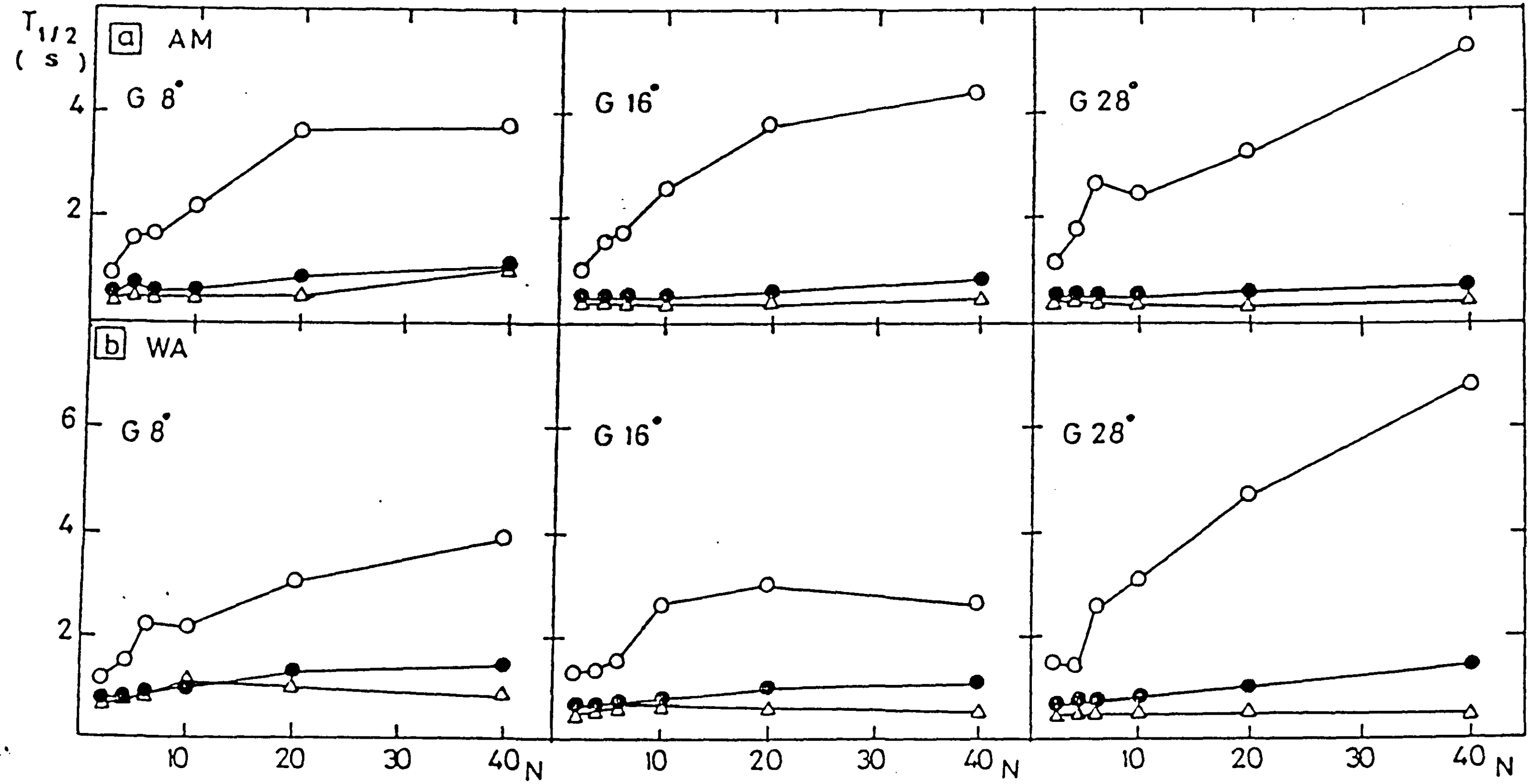

FIG. 4-10. Colour and orientation discrimination for square elements, with the target orientation specified on the plots. Results are for two subjects. Reference elements were ■ and ◆ both green (O); ■ green and ◆ red (●) and ■ green (Δ).

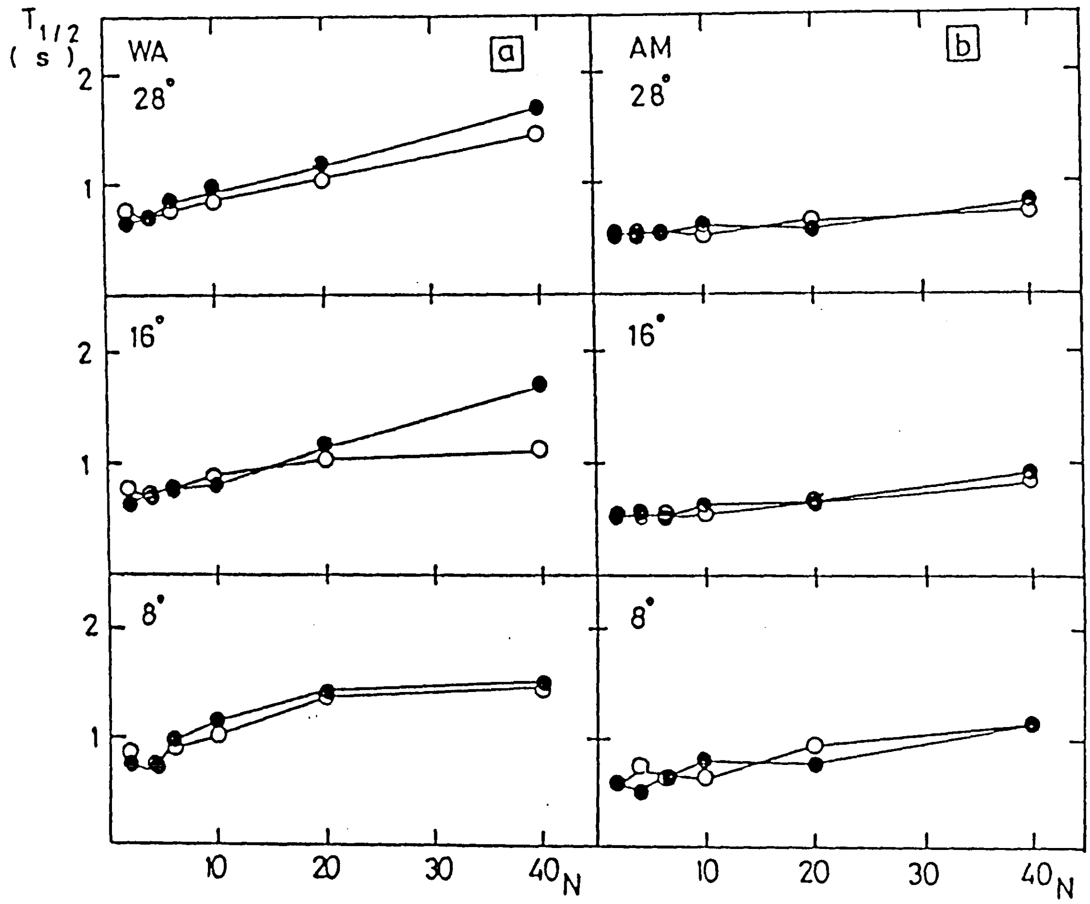

FIG. 4-11. Colour and orientation discrimination for square elements, with targets of orientation specified on the plots. Results are for two subjects. (O) Green targets with ■ green and ◆ red reference elements; (●) red targets with ■ red and ◆ green reference elements.

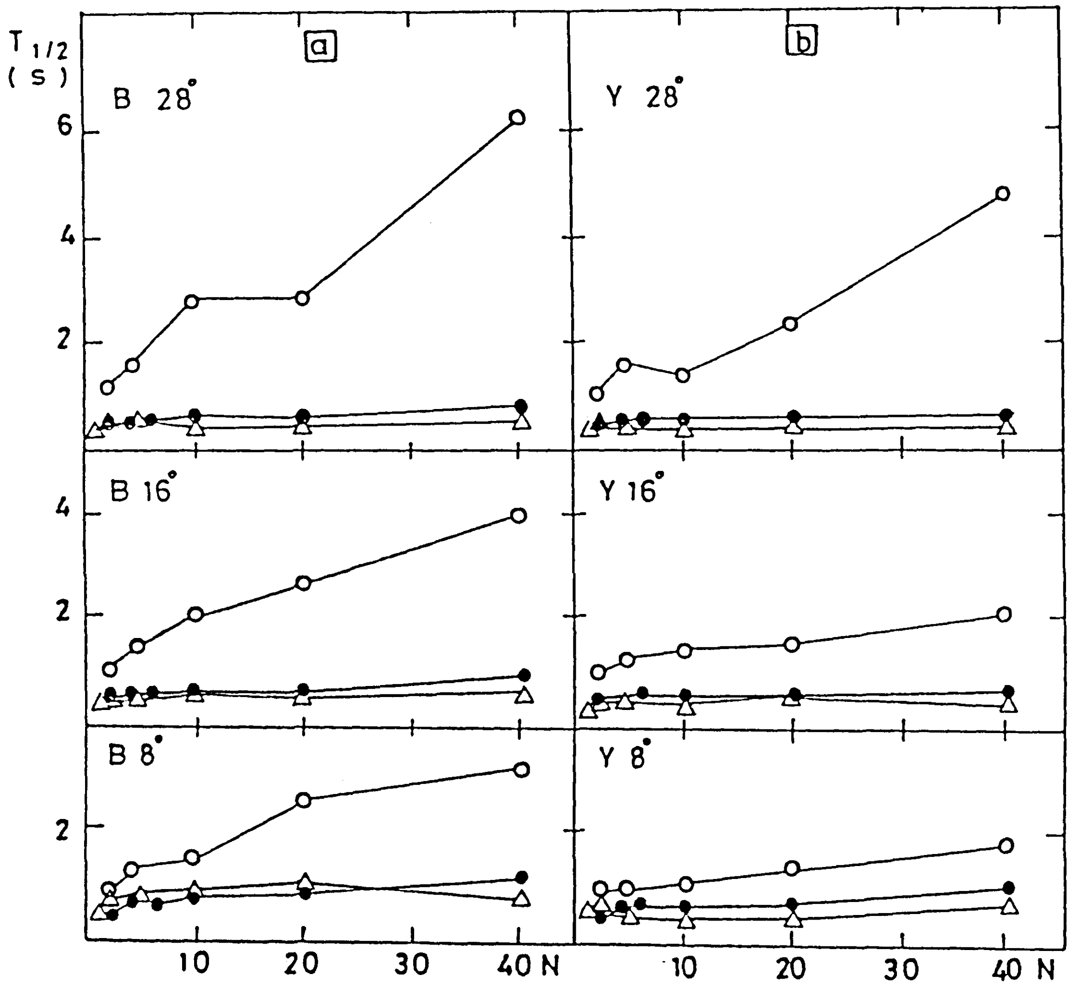

FIG. 4-12-b. Similar to Figure 4-12-a, but for subject AM.
(a) For blue targets.
(b) For yellow targets.

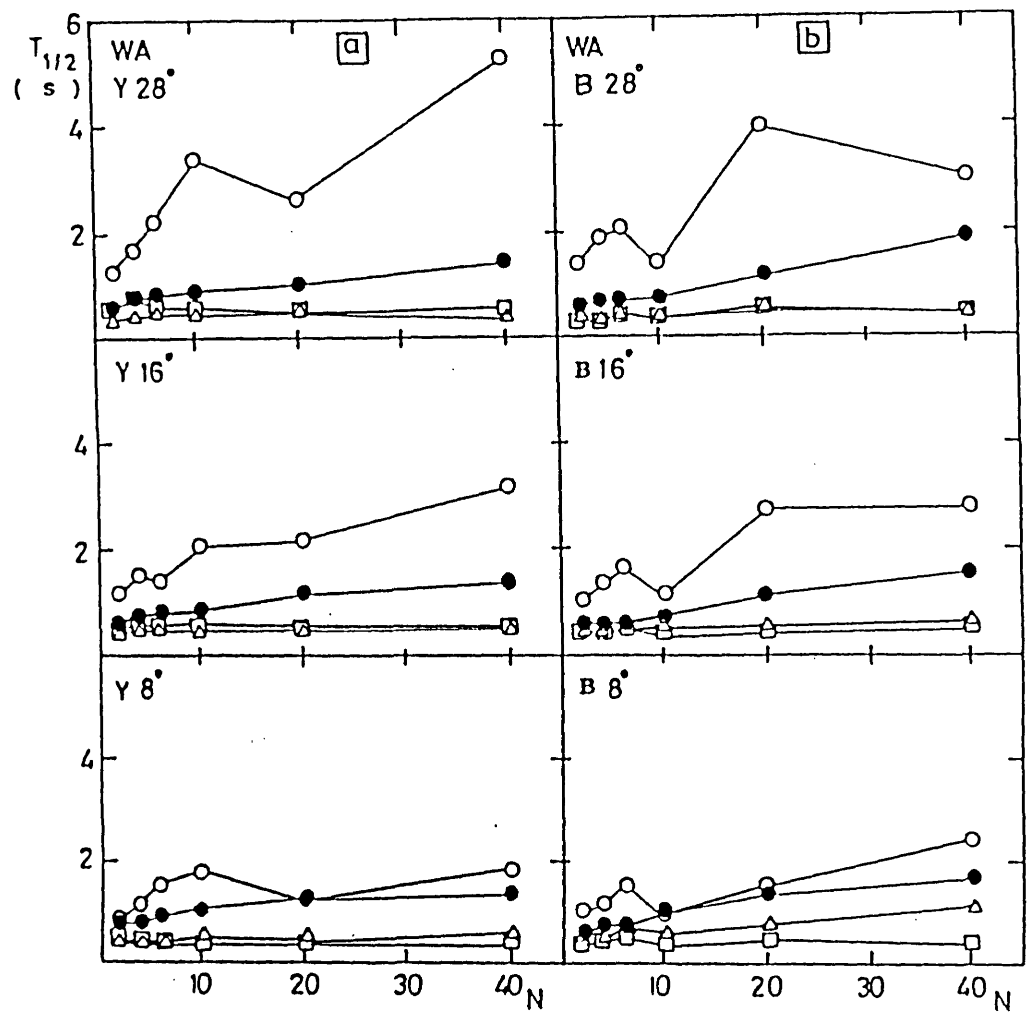

FIG. 4-12-a. Colour and orientation discrimination with square elements.
(a) For yellow targets with the orientation specified on the plot. The reference elements were: □ and ◇ yellow (O); □ yellow and ◇ blue (●); □ yellow (△) and ◇ yellow (□). (b) For blue targets with the orientation given on the plots. The reference elements were: □ and ◇ blue (O); □ blue and ◇ yellow (●); □ blue (△) and ◇ blue (□).

Thus, the experiments on orientation discrimination yield consistent data, showing that in making these discriminations, the visual system can largely ignore the elements which differ in colour from the target element.

4.5.1.B. <u>Discrimination of Magnification:</u>

Measurements were made to assess the influence of colour differences on the mechanisms responsible for discriminating differences in magnification. The experiments were organised in a manner similar to that described previously for orientation. Again, measurements were made with both triangular and square shaped targets and with the red-green and yellow-blue colour combinations, each pair being matched in luminance.

(i) <u>Equilateral Triangle:</u>

In these experiments, the relative linear magnifications of the reference elements were 83% and 33% and the targets, 100%, 50% and 25%.

The first set of data is given in Fig 4-13 showing the results for two subjects. The colour of the 83% reference elements and the targets were green, while the other, 33% reference elements, were either red or green. The $T_{\frac{1}{2}}$ values for detection of the target are greatly reduced with the two colour reference elements compared with the all green mixed reference elements. None the less, the $T_{\frac{1}{2}}$ values for two colour reference field are somewhat greater than those attained with a single class (green) reference element of size 83% (i.e. with the smaller elements completely absent).

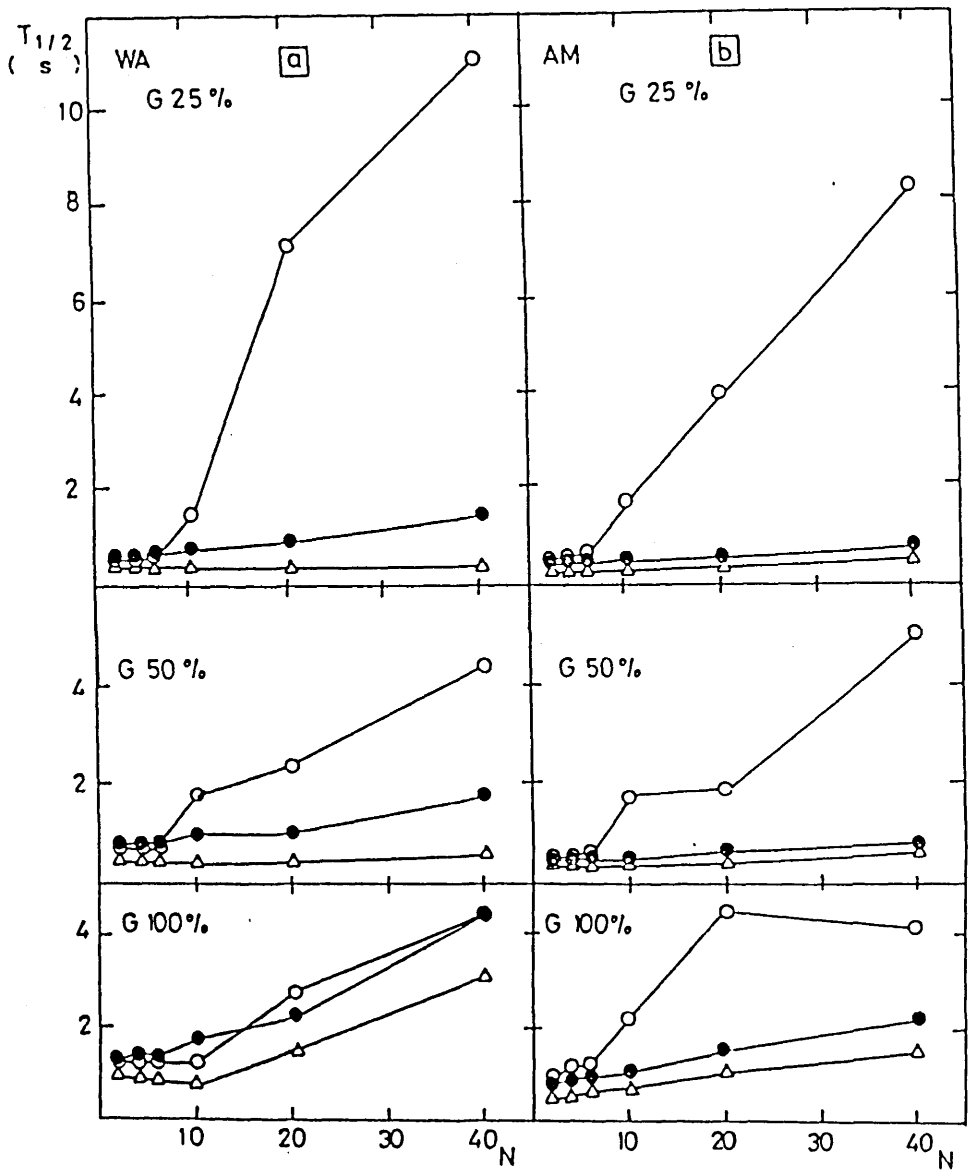

FIG. 4-13. Colour and magnification measurements for triangular elements. The targets were all green with relative linear magnification given on each plot. The reference elements were of linear size 83% and 33% and were all green (O); 83% and 33% red (●) and 83% green (Δ). Data for two subjects.

The way in which the relative colours of the reference and matching elements influence the results is illustrated further in Fig 4-14. In these experiments, the targets were red, but the reference fields with both combinations of mixed colours, i.e. large red (83%) and small green (33%) and large green (83%) and small green (33%) elements are examined. The results show that when the red target has magnification close to the red component of the reference field, $T_{\frac{1}{2}}$ values are large and increase significantly with N, whereas the green reference elements have little influence even when they are close in size to the red target.

Similar measurements were made for the yellow-blue combination and the results (Fig 4-15) are very similar to those obtained for the red green combination.

(ii) <u>Squares:</u>

In this set of experiments the targets were of relative linear size 100%, 50% and 25%. The two classes of reference element were of linear size either 80% and 30% or 60% and 33%, and all the coloured elements were of equal relative luminance. Data for the 60% green and 33% red reference elements are given in Fig 4-16. For comparison, results for all green mixed reference elements and the single 60% reference elements are also drawn. The targets are all green in colour. Results show that the 100% targets are discriminated in parallel for all reference fields.

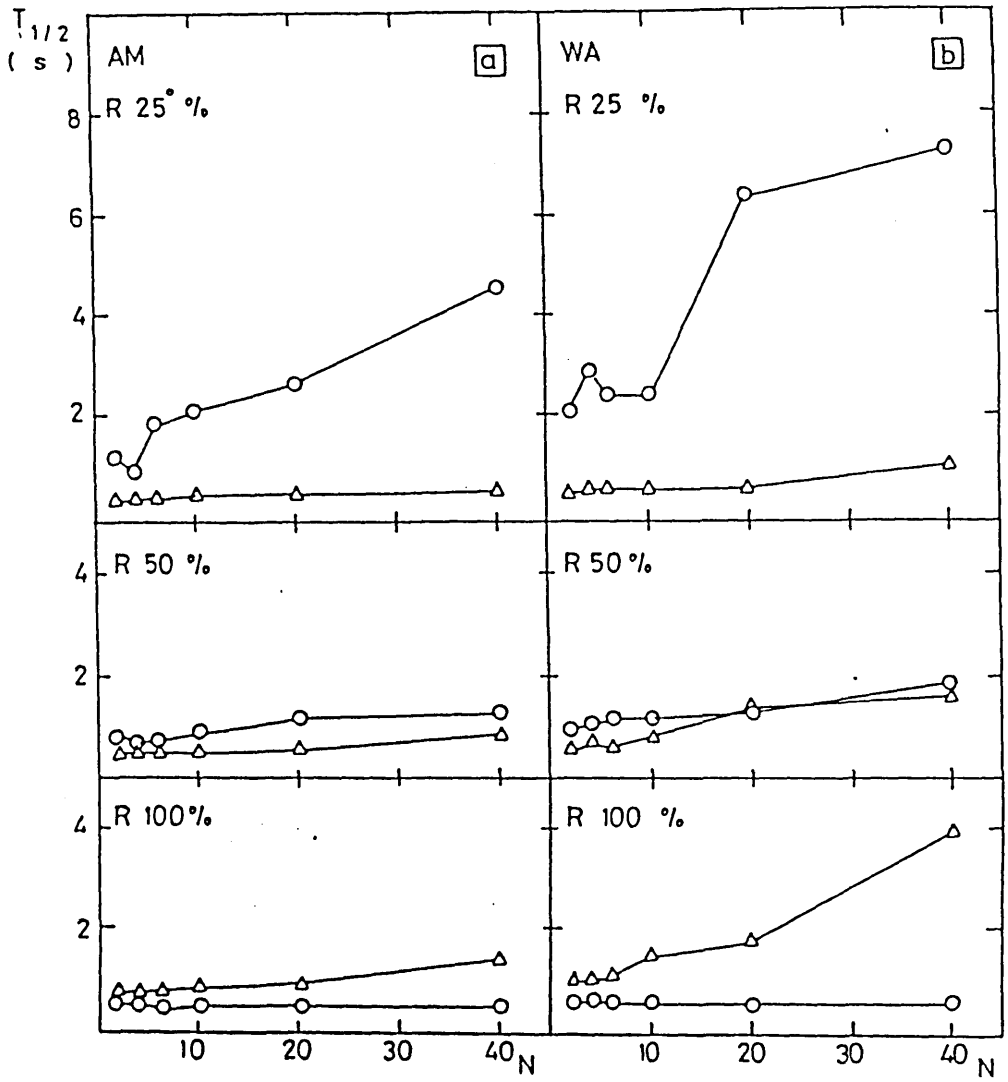

FIG. 4-14. Colour and magnification discrimination for red targets with linear magnifications given on each plot. The reference field consisted of triangular elements; 83% green and 33% red (O); 83% red and 33% green (Δ). Data for two subjects.

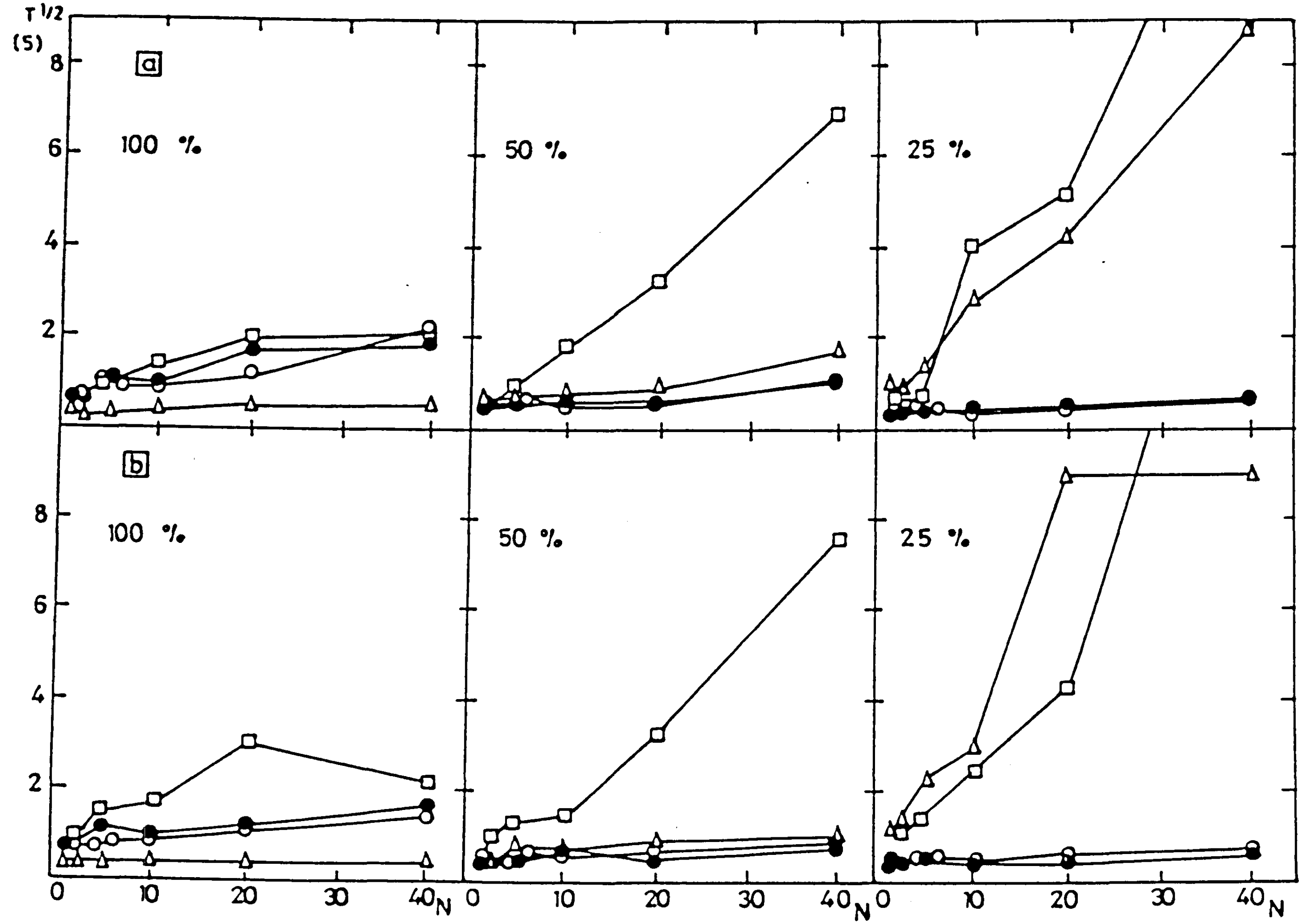

FIG. 4-15 . Colour and magnification discrimination measurements with triangular elements, as Figure 4-14, but for blue and yellow colours. (a) Blue targets from a reference field of 83% and 33% both blue, (□); 83% blue and 33% yellow, (○); 83% blue (●); 33% blue (△). (b) Yellow targets from a reference field of 83% and 33% both yellow, (□); 83% yellow and 33% blue, (○); 83% yellow (●); 33% yellow (△).

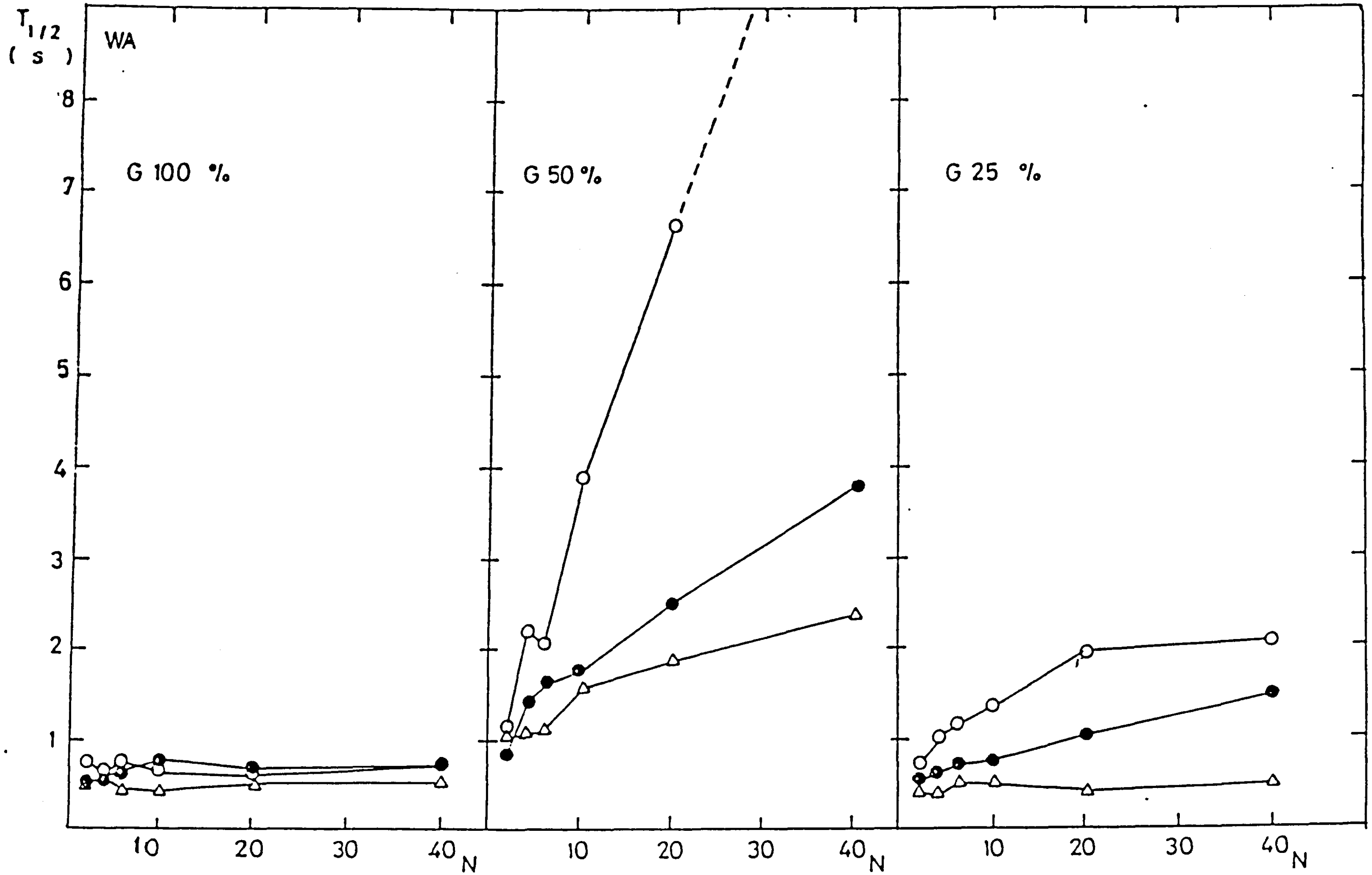

FIG. 4-16. Colour and magnification discrimination for square elements. The targets were green with magnification given on the plot. The reference elements were of size, 60% and 33% green (○); 60% green and 33% red (●); 60% green (△).

This is because the 100% target is much greater in size than both reference elements. The 50% target falls inbetween the two reference elements, of size 60% and 33%, and the discrimination process in this case is serial because the time of discrimination increases as the number of reference elements increases. If we compare the results for the mixed red and green reference field with the all green reference field we find that the $T_{\frac{1}{2}}$ values are lower for the mixed colour reference, but are still greater than those for fields constructed from a single class of element. Similarly if we compare the results for the 25% targets, we see that for the reference field constructed from a single class of element, discrimination is parallel but with mixed colour reference elements the $T_{\frac{1}{2}}$ values increase slightly with increase in the number of reference elements, but are still lower than those for the all green reference elements of mixed magnification.

Other experiments were performed with red targets and red and green reference elements which were interchanging in size between 60% and 33%. The results are shown in Fig 4-17 and show that the 100% target is discriminated by parallel processing for both reference field combinations. The 50% target is discriminated by serial process, and the values are greater when the reference field consisted of a mixture of 60% red and 33% green elements, than when it is composed of 60% green and 33% red elements. The reverse occurs with the 25% red target; discrimination is almost parallel when the red reference element is 60% but when the red reference element is 33% the $T_{\frac{1}{2}}$ values increase as N increases.

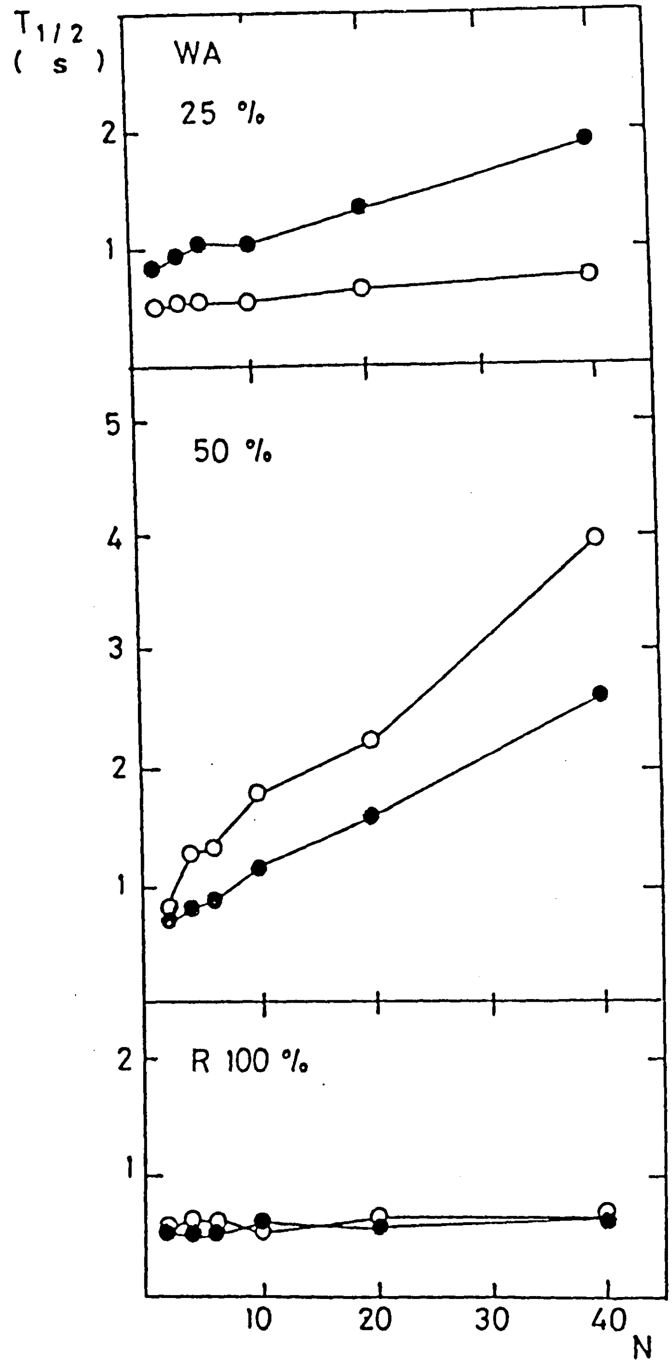

FIG. 4 – 17 . Colour and magnification discrimination for square elements with red targets of size given on the plots. The reference elements were of size 60% red and 33% green (O) and 60% green and 33% red (●).

Experiments with this combination of elements was repeated for the yellow and blue colours changing the colours of the two reference elements and the target. Results for these two experiments are shown in Fig 4-18. The graph shows that $T_{\frac{1}{2}}$ for discriminating the 50% target is by serial processing for both experiments, and the other two targets, 100% and 25% are discriminated by parallel processing.

Measurements were also made for reference elements of relative sizes 80% and 30%. Data obtained for the mixture of red and green reference elements is given for two subjects in Fig 4-19 and for all green mixed magnification and single magnification reference elements. Data for the mixed colour combination of reference elements and for both red and green targets are given in Fig 4-20. The results for the two target colours are similar. These results demonstrate again that changing the colour of one class of reference elements reduces significantly $T_{\frac{1}{2}}$ values, but they are still greater than those found with the single class of reference element.

4.5.2. Measurements with Equiluminance Stimuli:

Although the results of the previous sections establish that introduction of colour differences enables the visual system to neglect the non-matched stimuli in making spatial discriminations, the unmatched component of reference element still in some cases makes a contribution to the discrimination task. In the previous experiments the elements were presented on a black background and thus in addition to its colour contrast, each element also possessed a luminance contrast relative to the background.

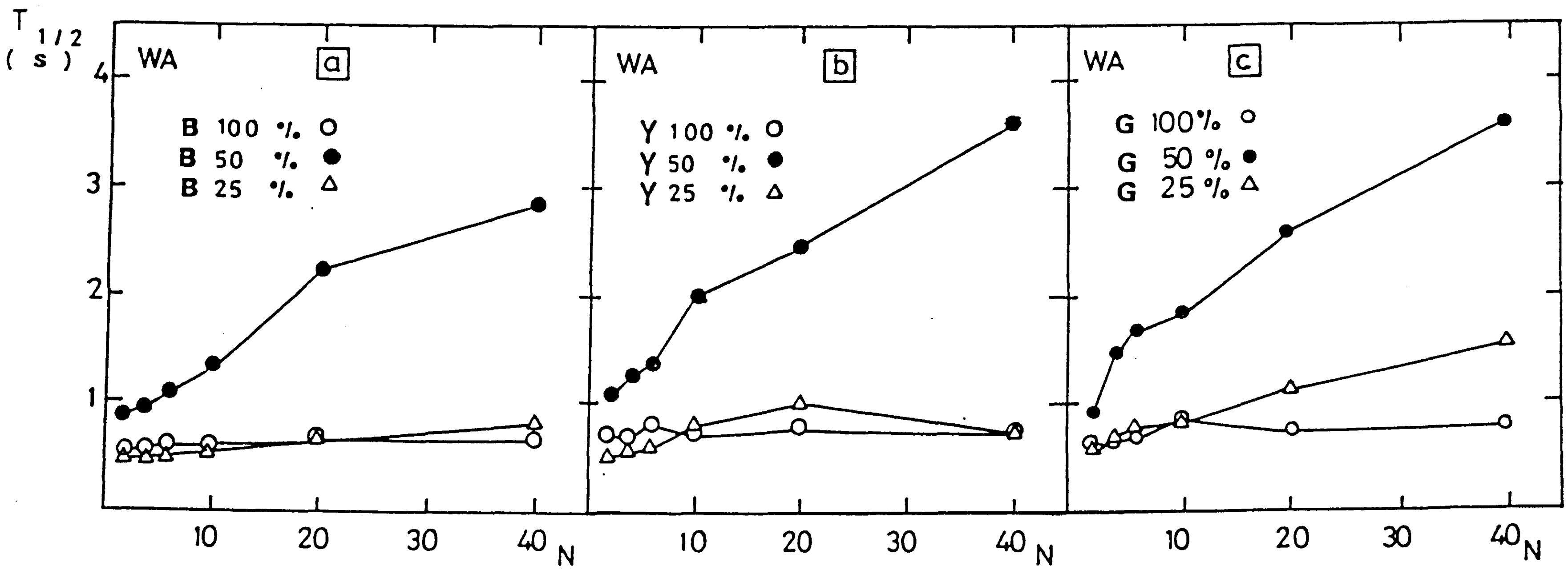

FIG. 4-18. Colour and magnification discrimination measurements for square elements:
(a) Blue targets, of size shown on the plot, with reference elements of size 60% blue and 33% yellow.
(b) Yellow targets, of size shown on the plot, with reference elements of size 60% yellow and 33% blue.
(c) Green targets, of size shown on the plot, with reference elements of size 60% green and 33% red.

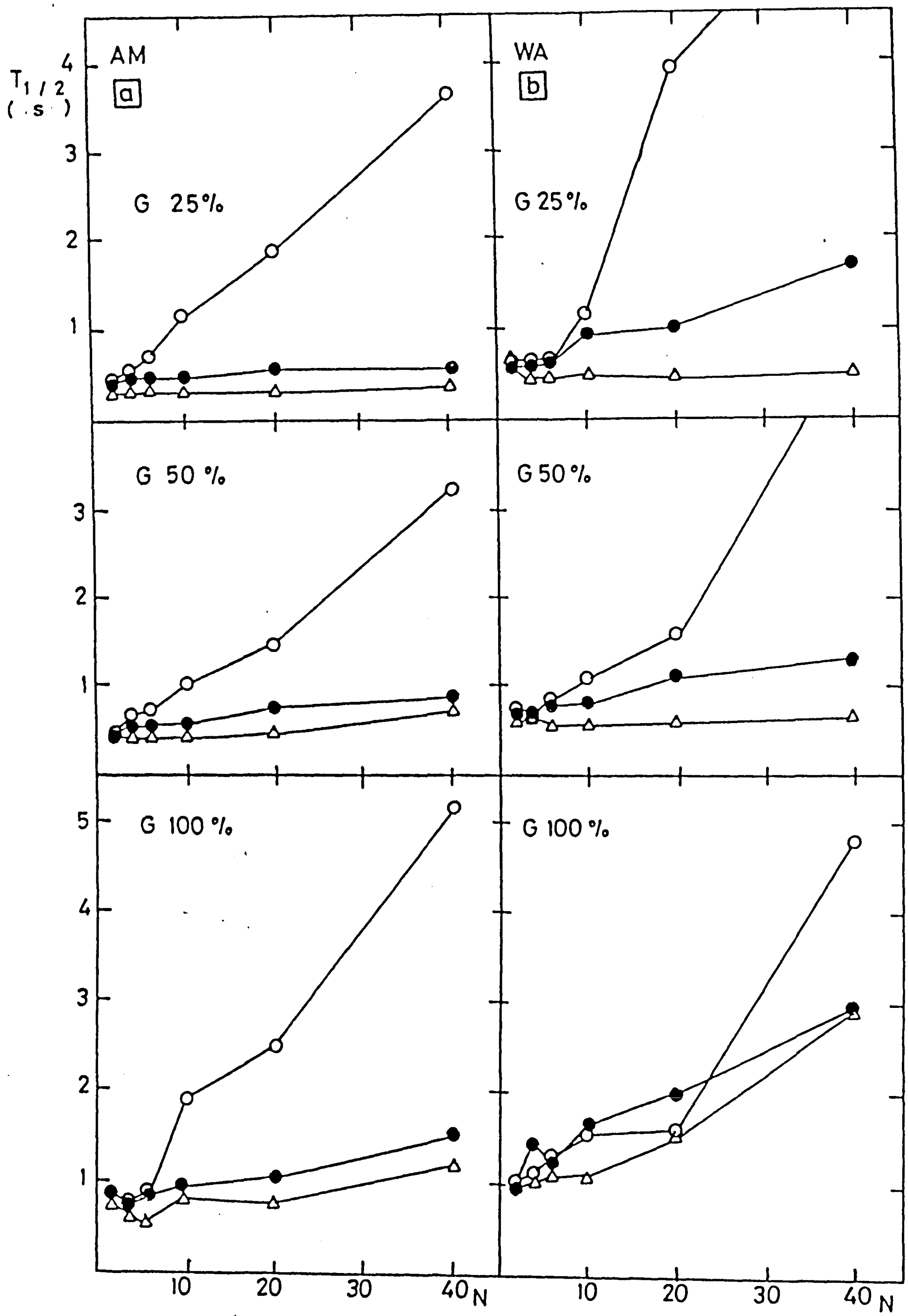

FIG. 4-19. Colour and magnification discrimination for square elements. The sizes of the green targets are given on the plots. The reference elements were of size 80% and 30% green (O); 80% green and 33% red (●); 80% green (△). Data for two subjects.

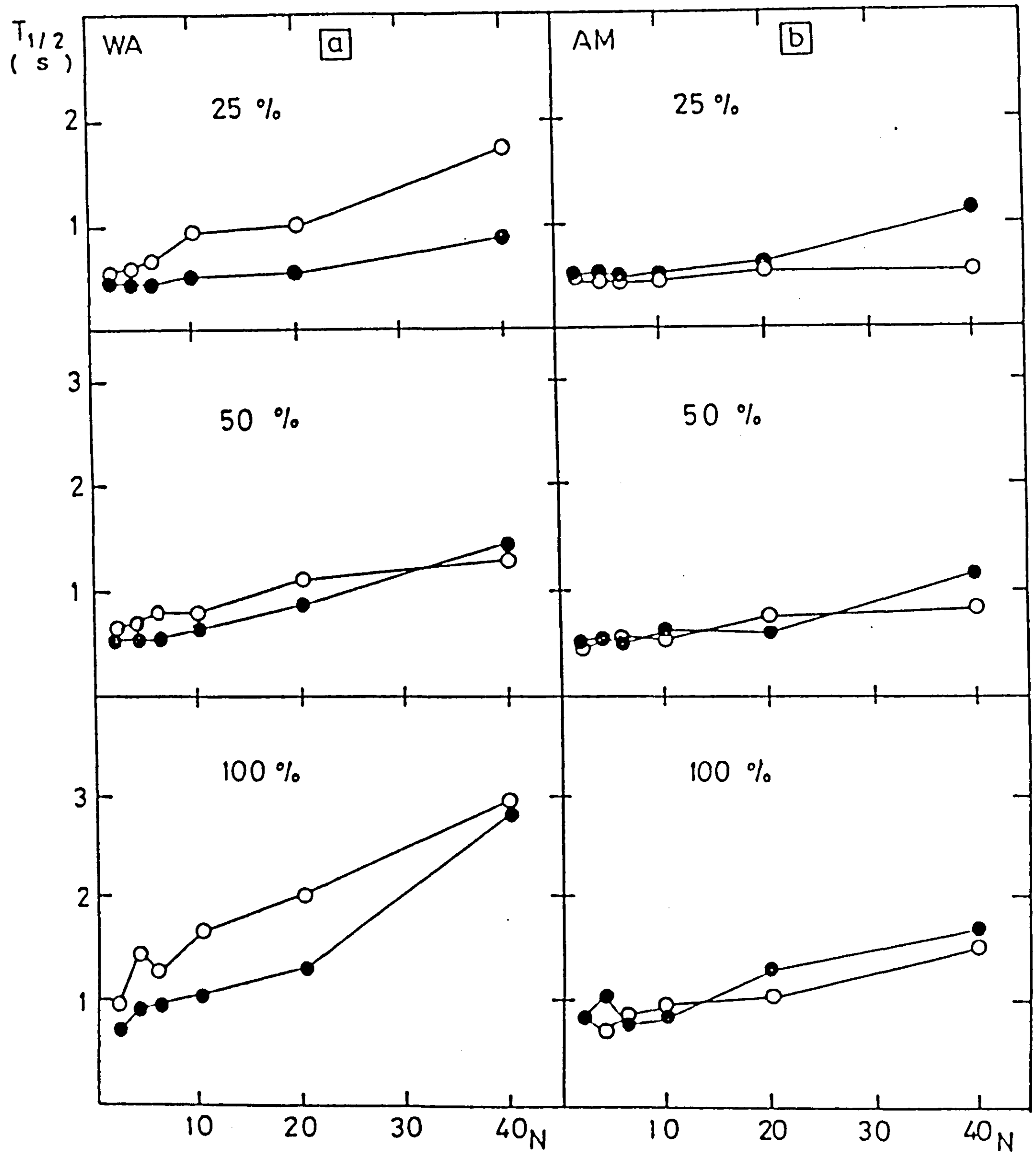

FIG. 4-20. Discrimination of colour and magnification for square elements. The targets were either red (O) or green (●), with sizes as marked on the plots. The reference elements were: 80% green and 33% red (O) or 80% red and 33% green (●). Data are given for two subjects.

In the experiments described in this section, the elements were presented at equiluminance with a background field, the chromaticity coordinates of which were intermediate between those of each coloured component used in the mixed reference fields. Thus, with a red and green combination of reference elements, the targets were superimposed on a yellow background, and with a yellow-blue combinations, the background was white (see Fig 2-7). It should be noted that the results for discrimination experiments with equiluminance fields are not significantly dependent on the relative luminances of the background and reference elements (Javadnia and Ruddock 1988b).

Orientation discrimination was measured for both colour combinations, with triangular targets. For the red-green combinations with yellow background, the difference between the $T_{\frac{1}{2}}$ values for the two colour mixed reference field, and that for the mixed reference field of green elements is very marked (Fig 4-21). The values for the mixed reference fields are, however, greater than those for the single class of reference element, despite the fact that there is no luminance step in this case. Similarly results are obtained for a combination of yellow and blue elements on a white background, (Fig 4-22).

Thus although the results for the red-green equiluminance system exaggerates the difference between the $T_{\frac{1}{2}}$ values for the two colours and the single colour reference fields relative to those found with the dark background, it does not appear that in general the non-matching colour component of the reference field can be entirely ignored.

A single set of measurements were also made for

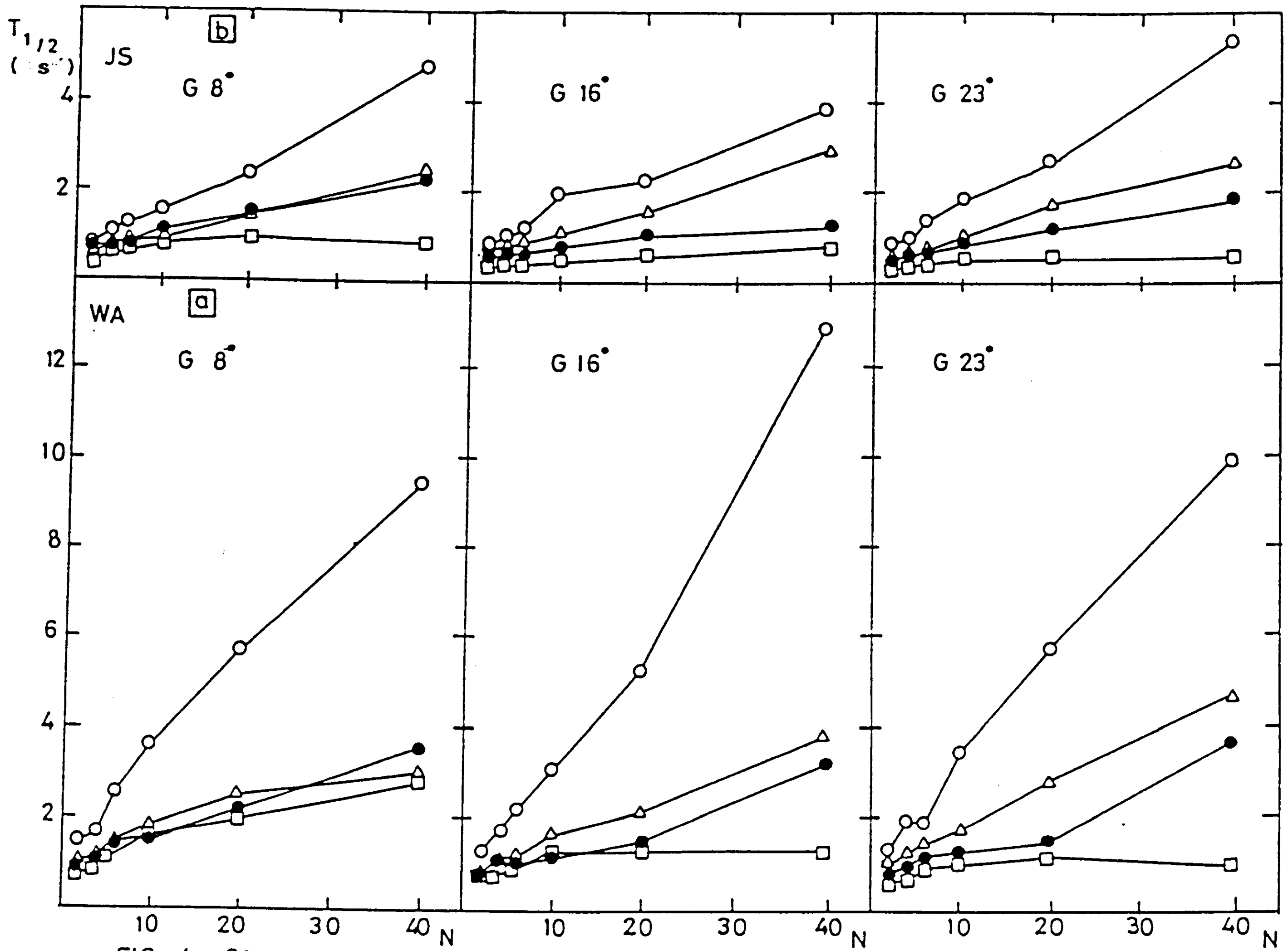

FIG. 4 _21. Colour and orientation discrimination for triangular elements, presented at equiluminance on a yellow background. The green targets were presented at the orientation indicated on the plots. The data refer to reference elements: ▲ green and ◀ green (O); ▲ red and ◀ green (Δ); ▲ green and ◀ red (●); and ▲ green (□). Data for two subjects.

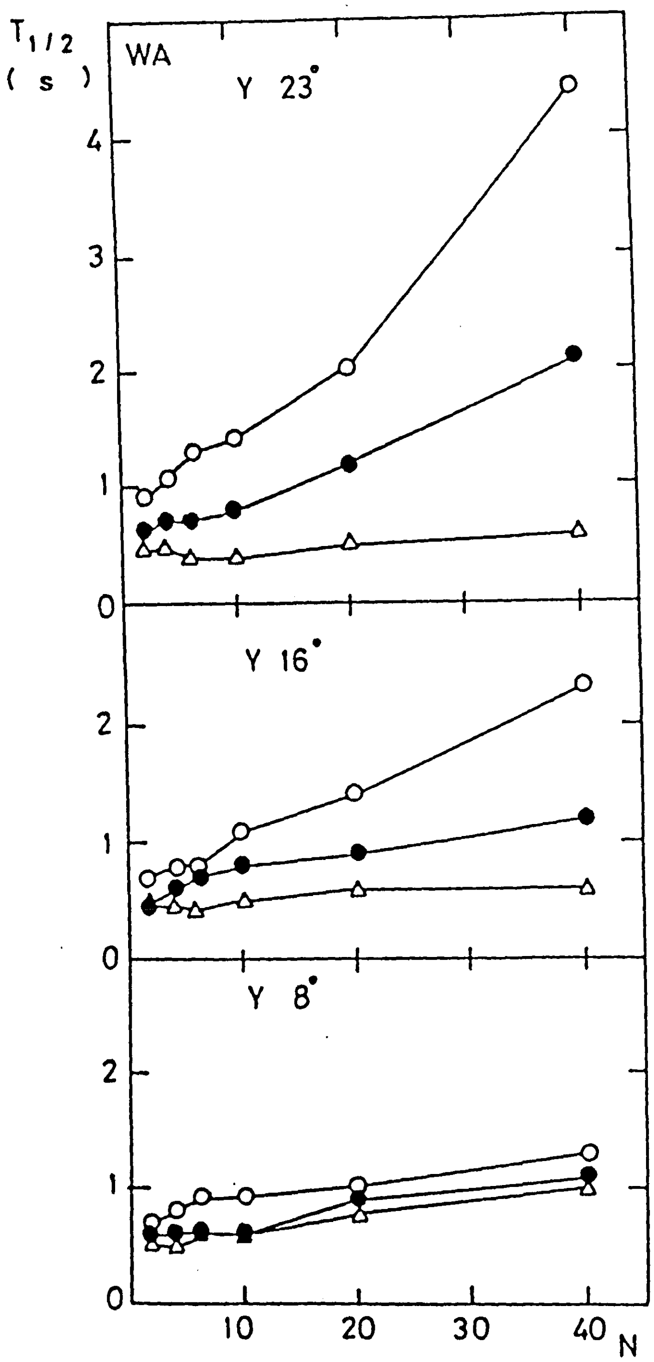

FIG. 4 _ 22. Colour and orientation discrimination for triangular elements presented at equiluminance on a white background. The yellow targets were presented at the orientation indicated on the plots. The data refer to reference elements ▲ yellow and ◀ yellow (O); ▲ yellow and ◀ blue (●); ▲ yellow (Δ).

magnification under equiluminance conditions, with red and green targets superimposed on a yellow background, all stimuli being maintained at equiluminance. The results are given in Fig 4-23, and show that, as in the previous measurement, the introduction of a colour difference into the mixed reference field reduces the value of $T_{\frac{1}{2}}$ relative to those obtained when both classes of reference elements are green. The values for the two colour reference field are in most measurements very similar to those obtained with the simple reference field containing only the 80% reference element, but are greater for the 100% target. Thus, this result again suggests that the separation between the differently coloured spatial elements is not complete.

4.5.3. Discrimination with Contrast Polarity:

In this section, I examine the effects of different contrast polarities on visual pattern discrimination. In order to do this, the reference elements were of two classes, one of positive contrast relative to a uniform background field and one of negative contrast. The general design of the experiments was very similar to that described in the previous section on colour, with measurements made for a mixture of e.g. two orientations of different polarity compared with those of the same polarity, and with a simple reference field containing only one orientation of a single polarity.

4.5.3.A. Orientation Measurements:

Results are given separately for triangles and square elements.

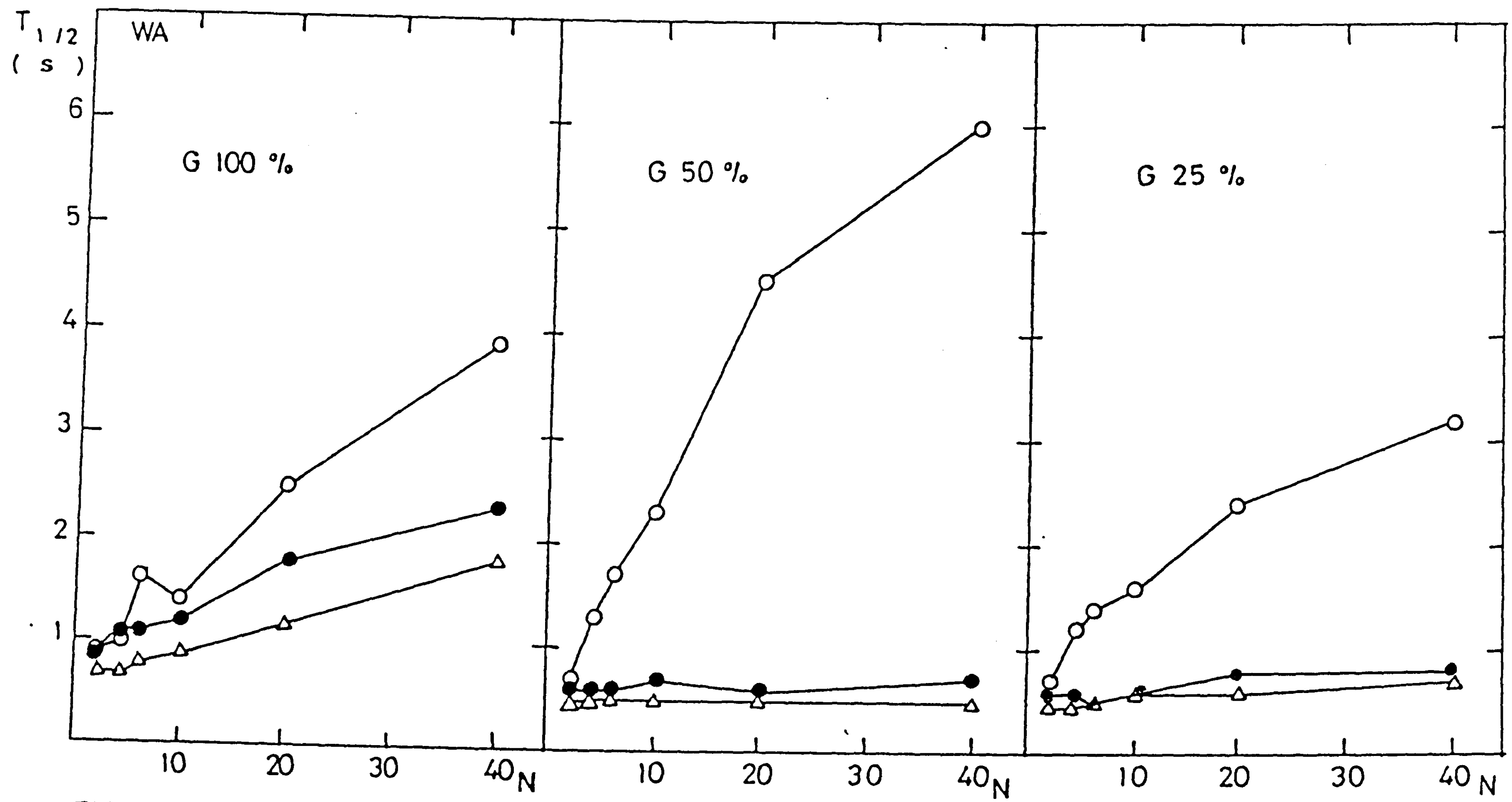

FIG. 4 - 23. Colour and magnification discrimination measurements for square elements presented at equiluminance on a yellow background. The green targets were of relative magnification indicated on the plots. The reference elements were of size and colour 80% green and 33% green (O); 80% green and 33% red (●); and 80% green (Δ).

(i) <u>Equilateral Triangles:</u>

Experiments were performed with two classes of reference elements, one pointing upwards and the other rotated through 30 deg. in a clockwise direction, with target orientations of 8 deg., 16 deg. and 23 deg. The relative luminance of the background field was 1.0

In the first set of data, the target was of positive contrast polarity, 1.23 relative luminance, and the two classes of reference elements were of positive and negative contrasts, 1.23 and 0.77 relative luminance respectively, giving a contrast levels of ±0.23. Results given in Fig 4-24, for two observers, show that $T_{\frac{1}{2}}$ values are lower when the reference field is composed of the mixture of the two contrast polarities than when it is composed of one positive class and one negative class. The values for mixed contrast reference fields are, however, greater than those for the simple fields consisting of only upright triangles.

Similar data, in which targets were of negative contrast with relative luminance of 0.77, are given in Fig 4-25 for two subjects, with the equivalent combinations of reference elements (i.e. mixed polarity, all negative contrast and simple field, with negative contrast). The results are in general, similar to those obtained for the positive contrast targets, but for the smallest (8 deg.) target orientation, there is little difference between the $T_{\frac{1}{2}}$ values of the different contrast polarities, because even with the mixed reference field of negative contrast there is only a small increase relative to the simple field.

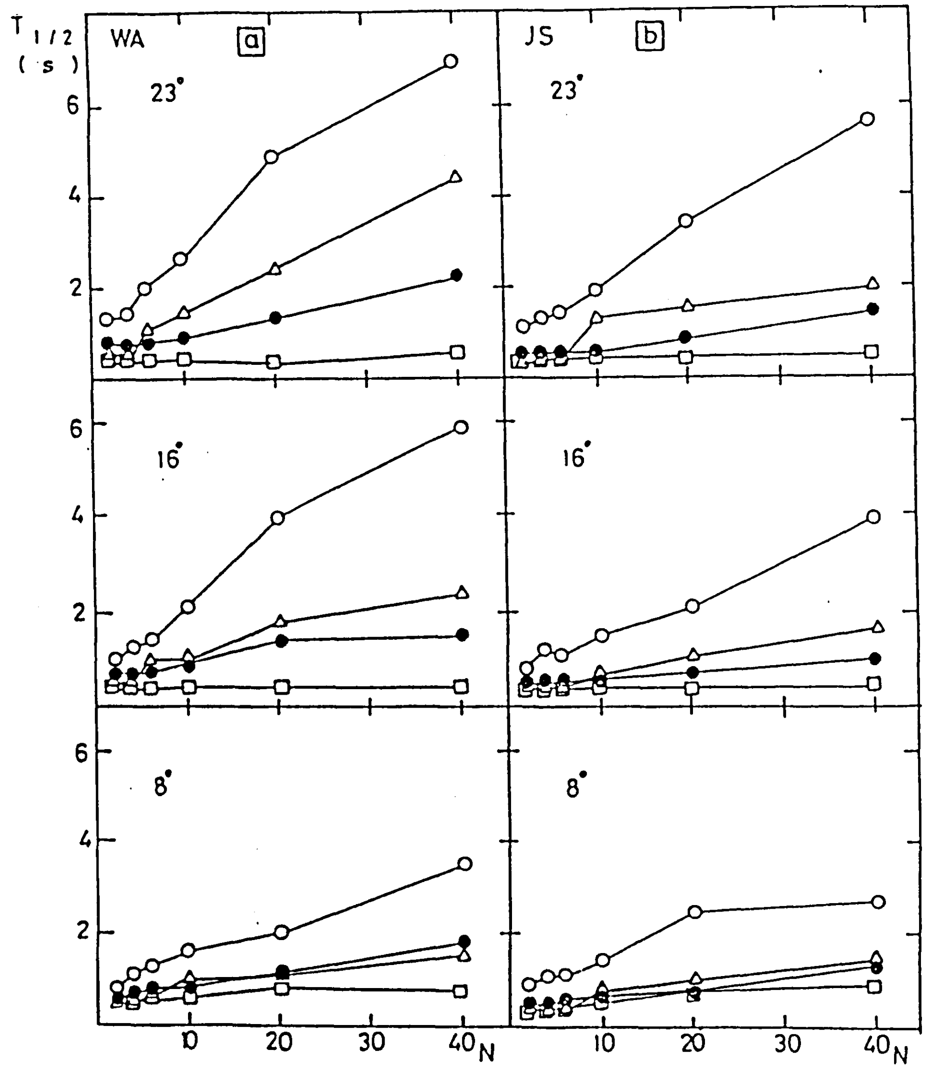

FIG. 4-24. Orientation discrimination for different contrast polarities in the reference field. The triangular elements were presented on a background of relative luminance 1.0, and the targets were of relative luminance 1.23, and presented at the orientations noted on the plots. The reference elements were: ▲ and ◀, with relative luminance 1.23 (○); ▲, 1.23 and ◀, 0.77 (●); ▲, 0.77 and ◀, 1.23 (△); ▲, 1.23 (□).

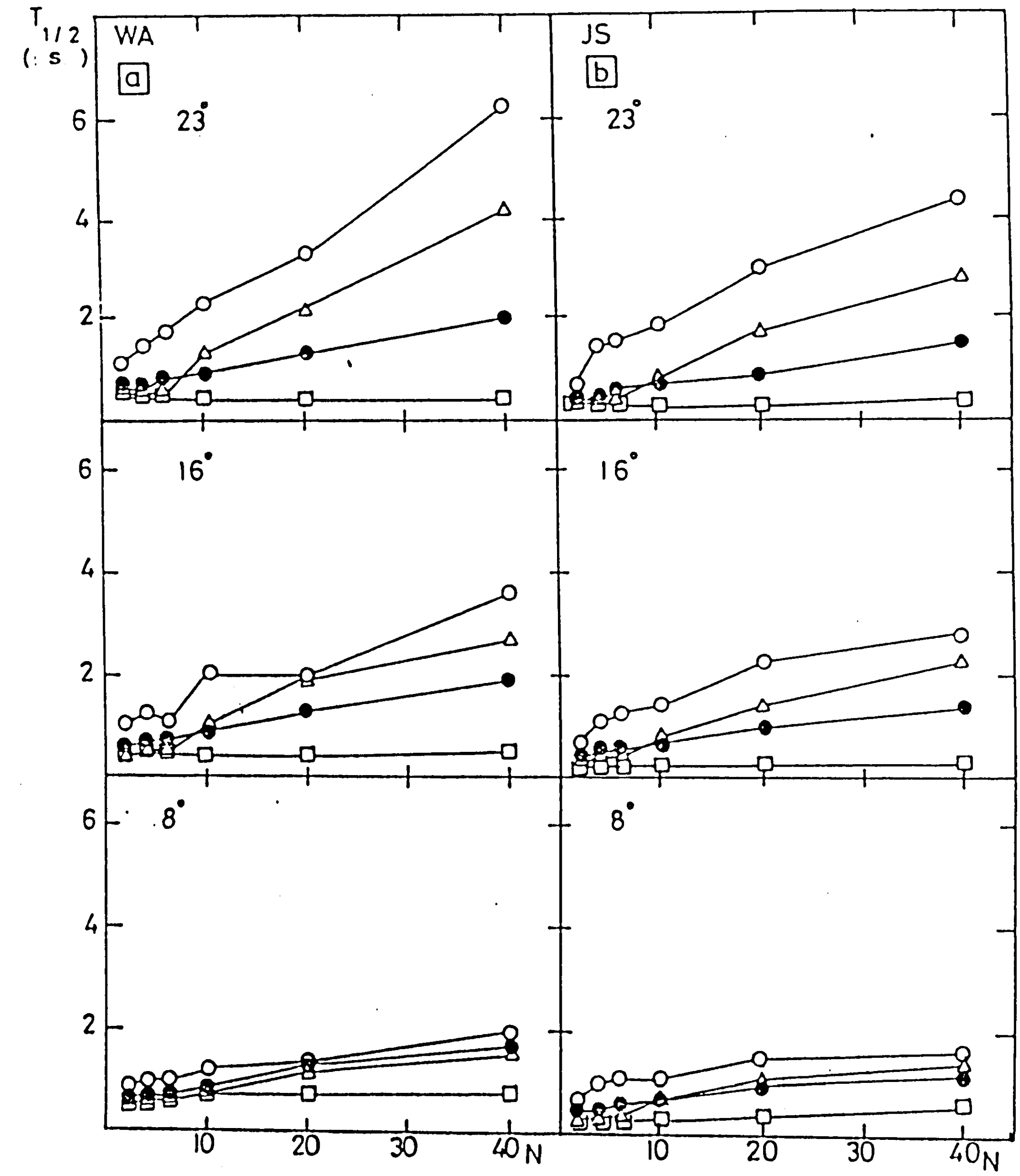

FIG. 4-25. As Figure 4-24, but for targets of negative contrast (0.77). The reference elements were ▲ and ◀, 0.77 (○); ▲, 0.77 and ◀, 1.23 (●); ▲, 1.23 and ◀, 0.77 (△); and ▲, 0.77 (□).

Further results were obtained with a larger contrast step. The target was of positive contrast (Fig 4-26a), with relative luminance 1.43, and the reference elements were either of positive or negative polarity, their relative luminance values being 1.43 and 0.57 respectively. The experiment was also performed with target of negative contrast polarity and the results are given in Fig 4-26b. The results show that when the target is distinguished from reference fields of similar contrast, $T_{\frac{1}{2}}$ tends to be greater in value than when it is distinguished from reference field of mixed polarity contrasts. The differences, however, are less well defined than those obtained with the lower contrast levels.

(ii) <u>Squares:</u>

Measurements for orientation discrimination with reference elements of different contrast polarity were made for one class orientated in the upright position and the other 45 deg. to the vertical. The target orientations were 8 deg., 16 deg. and 28 deg. relative to the vertical. The background was of relative luminance 1.0 and the targets were for some experiments of relative luminance 0.77 and for others of relative luminance 1.23, i.e. they had polarity contrasts ±0.23. The reference fields consisted of all positive, all negative or a mixture of positive and negative polarity contrasts set at contrast levels ±0.23. The results are shown in Fig 4-27, which gives $T_{\frac{1}{2}}$ values for each case and for reference fields consisting of only upright elements. It is noted that $T_{\frac{1}{2}}$ value for targets of the same contrast polarity as the reference fields are higher than

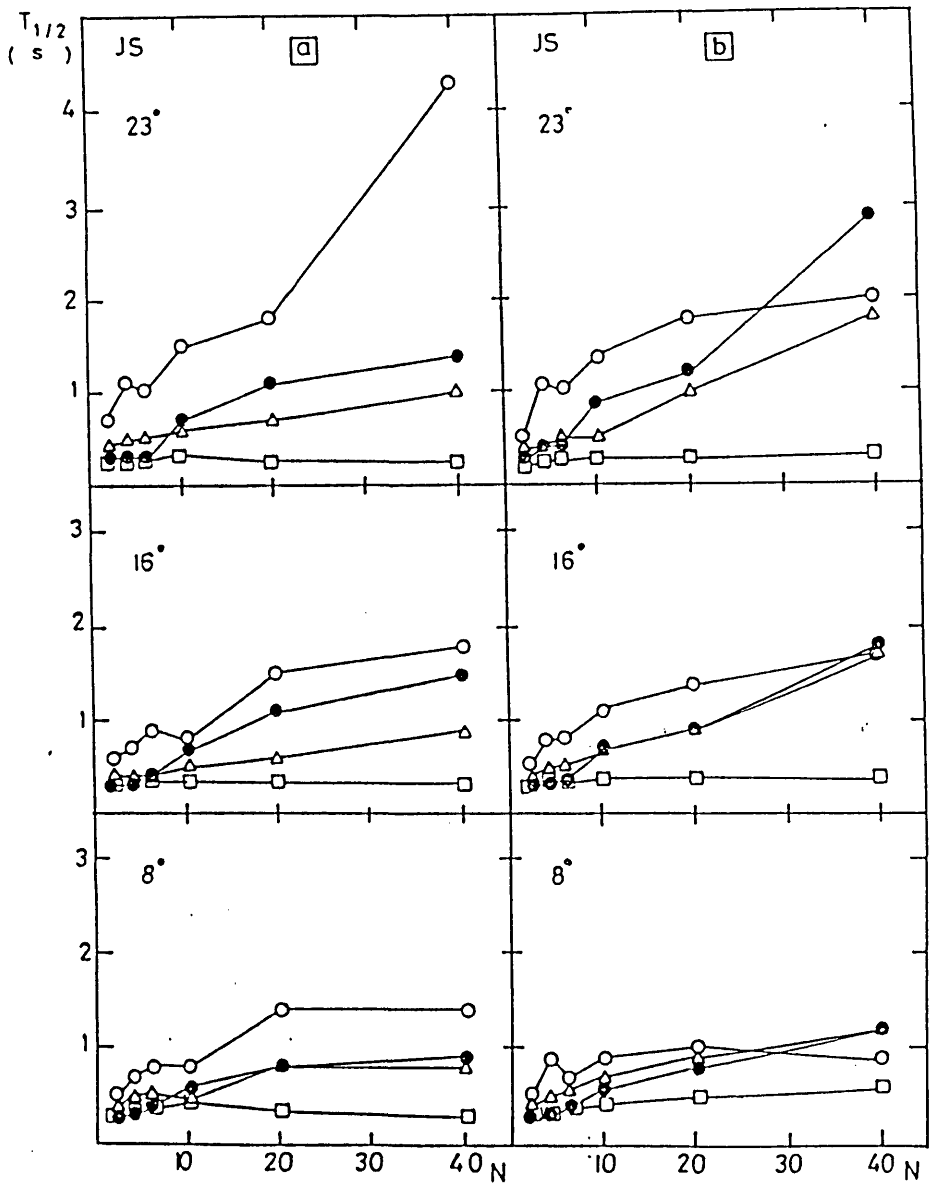

FIG. 4-26. As Figure 4-24, but (a) for targets of luminance 1.43 and reference elements as follows: ▲ and ◀, 1.43 (○); ▲, 0.51 and ◀, 1.43 (●); ▲, 1.43 and ◀, 0.51 (△); and △, 0.51 (□). (b) for targets of luminance 0.51 and reference elements: ▲ and ◀, 0.51 (○); ▲, 1.43 and ◀, 0.51 (●); ▲, 0.51 and ◀ 1.43 (△); and ▲, 1.43 (□).

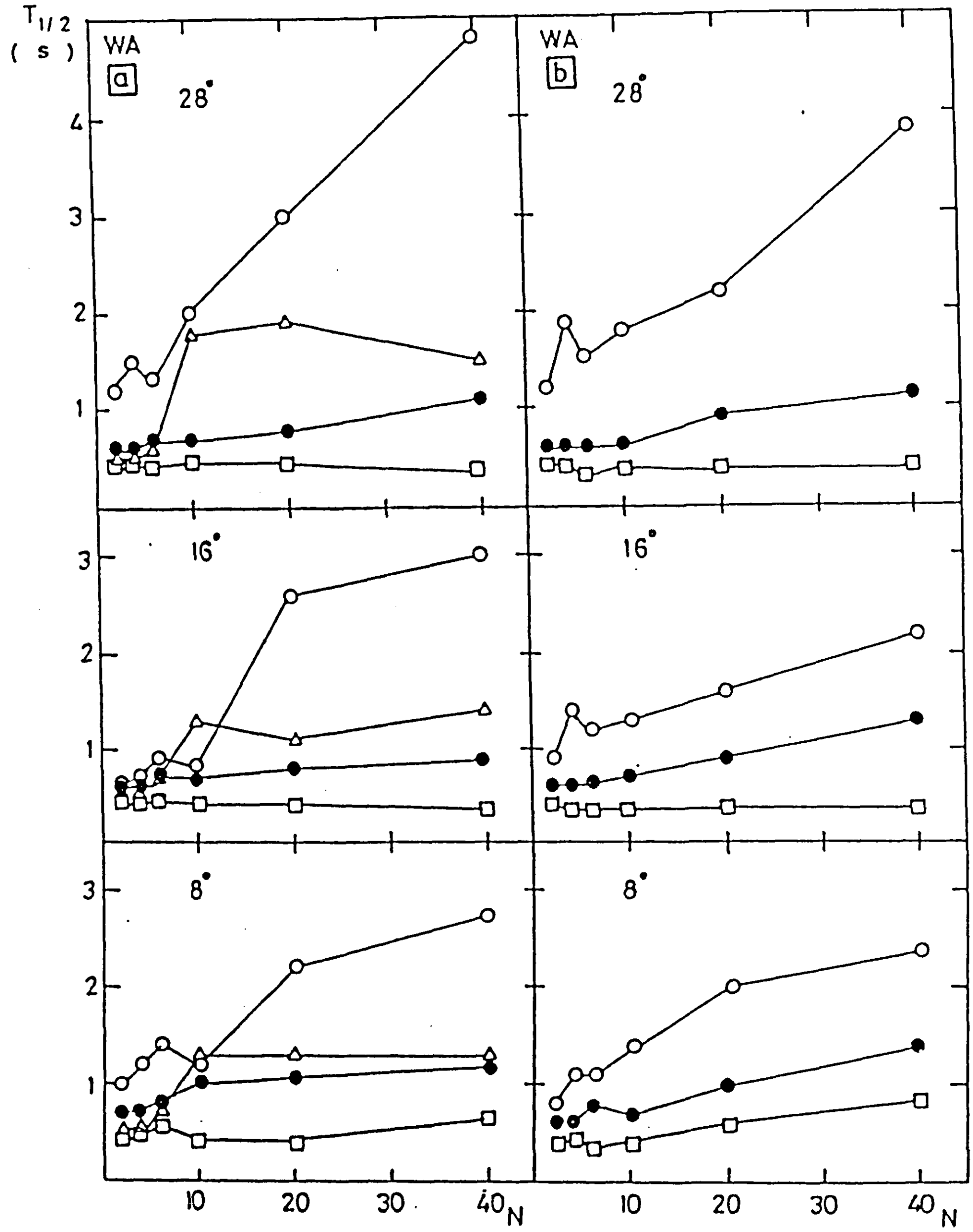

FIG. 4-27. As Figure 4-24, but for square elements, with targets of orientation angle shown on the plots. (a) Targets of positive contrast, with relative luminance 1.23. The reference elements were ■, 1.23 and ◆, 1.23 (○); ■, 1.23 and ◆, 0.77 (●); ■, 0.77 and ◆, 1.23 (△); ■, 1.23 (□). (b) Targets of negative contrast, with relative luminance 0.77. The reference elements were ■, 0.77 and ◆, 0.77 (○); ■, 0.77 and ◆, 1.23 (●); ■, 0.77 (□).

those when the reference field is composed of a mixture of positive and negative contrast polarity, although the values for the mixed contrast fields are greater than those for the simple fields consisting of a single class of element. A second set of values of contrast polarity were also examined, with elements of relative luminance 1.43 and 0.51 and background of relative luminance 1.0 (i.e. the relative positive contrast polarity was +0.43 and the negative contrast polarity was -0.49). The mixed fields were composed of both positive and negative contrast polarity or either one of them separately, and data were also obtained for a simple field consisting of a single class of reference element. Results for these experiments are given in Fig 4-28. Again $T_{\frac{1}{2}}$ values for target recognition in the reference field consisting of the same contrast polarity as the target are higher than when the reference field was a mixture of both positive and negative contrast polarities, although the differences are less marked than for the lower contrast data because the values for the mixed orientation reference field of a single contrast are lower.

A further set of experiments were performed with different elements, which were designed to correspond to stimuli used in electrophysiological studies of the striate cortex. One consisted of a central bar which had either positive or negative contrast with the surround bars (Fig 2-9) of opposite contrast and was equivalent to the bar shaped stimuli used by Hubel and Wiesel (1962, 1968) to investigate orientation selective responses of neurons with bar shaped receptive fields.

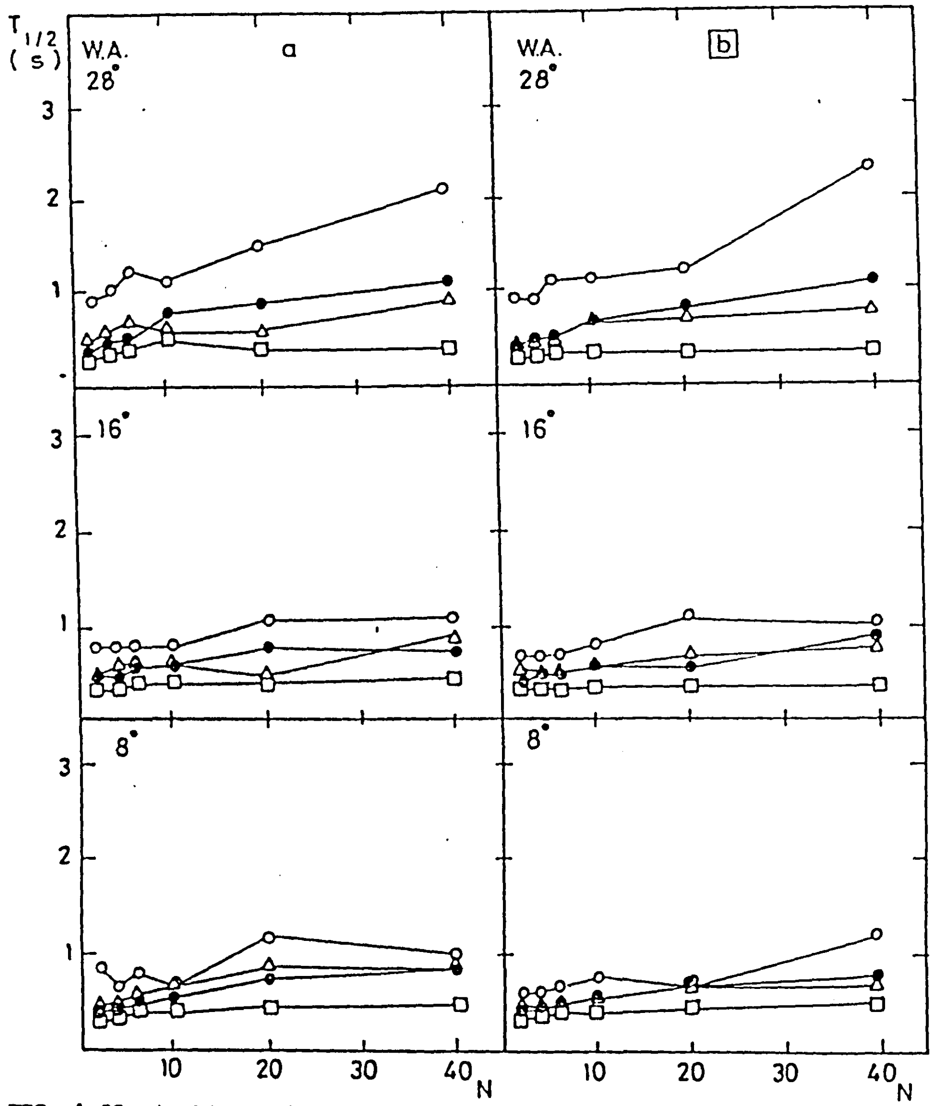

FIG. 4-28. As Figure 4-27, but for higher contrasts. (a) The target illumination was 1.43 and the reference elements ■ , 1.43 and ◆ , 1.43 ( ); ■, 0.51 and ◆, 1.43 (●); ■, 1.43 and ◆, 0.51 (△); ■, 1.43 (□). (b) The target illumination was 0.51 and the reference elements ■, 0.51 and ◆, 0.51 (○); ■, 1.43 and ◆, 0.51 (●); ■, 0.51 and ◆, 1.43 (△); ■, 0.51 (□).

The second set consisted of edges, which divided square elements into two halves, one of positive and one of negative contrast with respect to the background field. These elements correspond to those used by Hubel and Wiesel (1962, 1968) in their measurements on orientation responses of edge sensitive neurons.

Data for the edge shaped stimuli were obtained with three different reference fields; two mixed with two different edge orientations which were either of the same or of reversed polarity and the third consisting of only one edge orientation. The results (Fig 4-29a) show that although mixing the two polarities reduces somewhat the effects of the mixed reference field, $T_{\frac{1}{2}}$ values are still much greater than those obtained with only one reference orientation. The square element set of reference fields were also examined in the case of the bar-shaped stimuli and the results are similar to those obtained with the edges (Fig 4-29b). Again introducing a mixed contrast in the reference field causes only a moderate reduction in the $T_{\frac{1}{2}}$ values. Thus these results do not provide strong evidence for the activity of orientation selective mechanisms, which respond specifically to either positive or negative contrast, as described by Hubel and Wiesel (1962, 1968).

In fact, the first experiments with simple contrast patterns give more conclusive evidence of sensitivity to contrast polarity than do those with these "biological" stimuli.

4.5.3.B. <u>Magnification Measurements with Square Elements:</u>

In the study of magnification discrimination described in previous chapters,I showed that results for the two

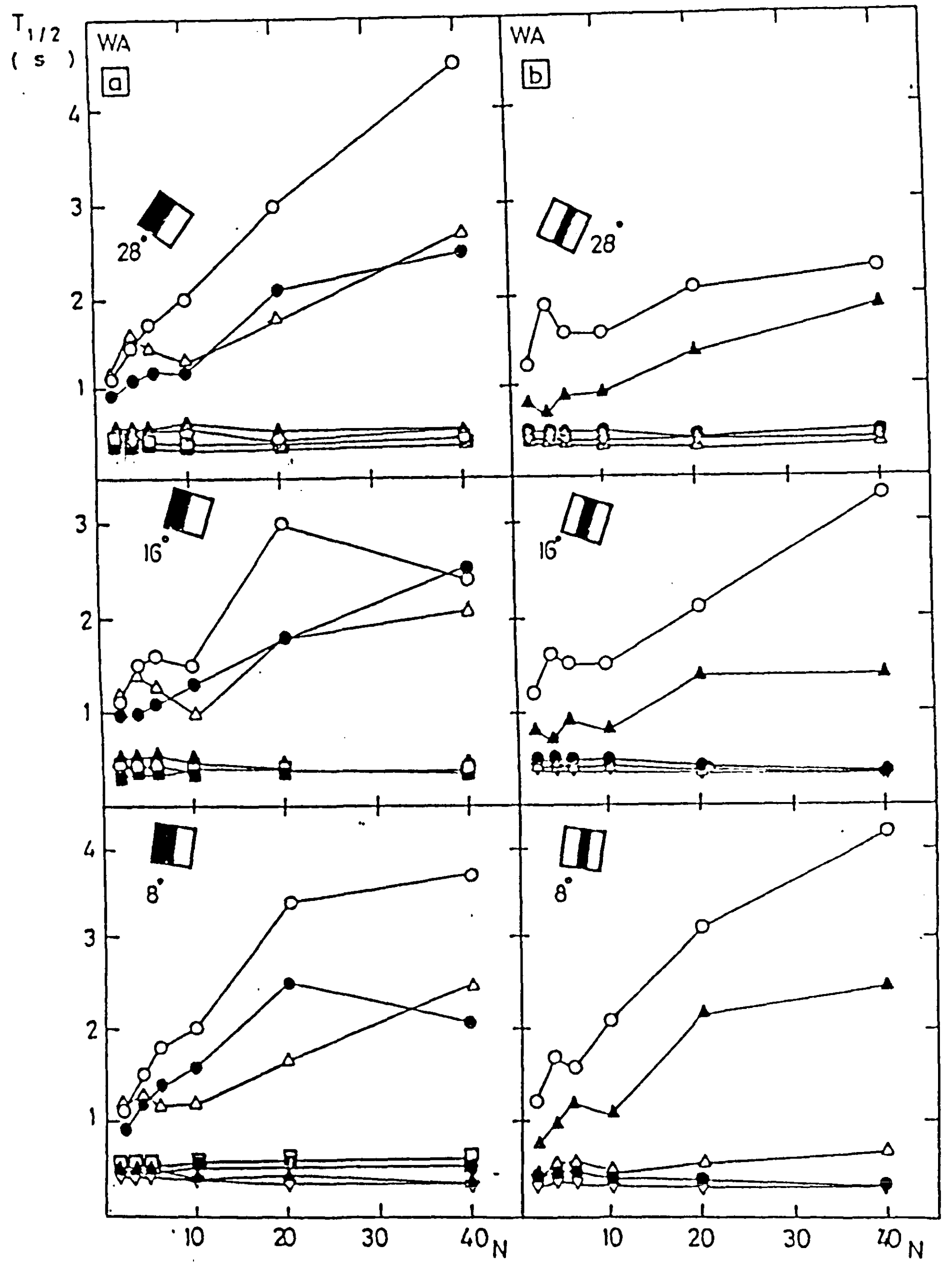

FIG. 4-29. Orinetation discrimination for bar and edge shaped elements, with various combinations of contrast polarity. The elements were presented on a background of relative illumination 1.0, and the dark and light shaded areas of the elements were of relative illumination 1.23 and 0.77 (a) Data for edges, with the targets oriented as indicated on the plots. The reference elements were: ◧ and ◆ (○); ◧ and ◆ (●); ◨ and ◆ (△); ◆ (▲); ◆ (▽); ◧ (■); ◨ (□). (b) Data for bars, with the targets oriented as indicated on the plots. The reference elements were: ◫ and ◈ (○); ◫ and ◆ (▲); ◈ (●); ◆ (▽); and ◫ (△).

geometrical shapes, squares and triangles, are very similar to each other. Therefore, in this section I used only squares to study the effect of contrast polarity on the discrimination of the target from a reference field of mixed magnification and with positive and negative contrasts polarity.

The contrast polarities of the reference elements were ±0.23 and results were obtained for targets of positive polarity with relative sizes of 75%, 60% and 45% presented in a reference field of relative sizes of 100% and 25%. Results are given in Fig 4-30 (for two subjects) and it is seen that $T_{\frac{1}{2}}$ values are greater when the reference field and the target are all of positive contrast than when the reference fields are of mixed contrast polarity, although the differences are not large because visual performance is relatively good in all cases. The $T_{\frac{1}{2}}$ values for the mixed contrast reference fields are similar to those obtained when the reference field is composed of only one class of element (25% or 100% squares).

Similar results were obtained with the same dimension of elements but with targets of negative polarity (Fig 4-31, for two subjects) and for higher contrast levels, equal to +0.43 and -0.49 (Figs 4-32 and 4-33).

The parameters chosen in the last section do not show the specificity of responses to contrast polarity as clearly as those for orientation specificity. Thus another set of experiments are performed with reference elements of 80% and 31% linear size and the targets sizes are 100%, 50% and 25%. Data for positive and negative contrasts (±0.23 relative contrast) show that (Fig 4-34) when the reference field was all of positive or all negative contrast elements, $T_{\frac{1}{2}}$ values for target

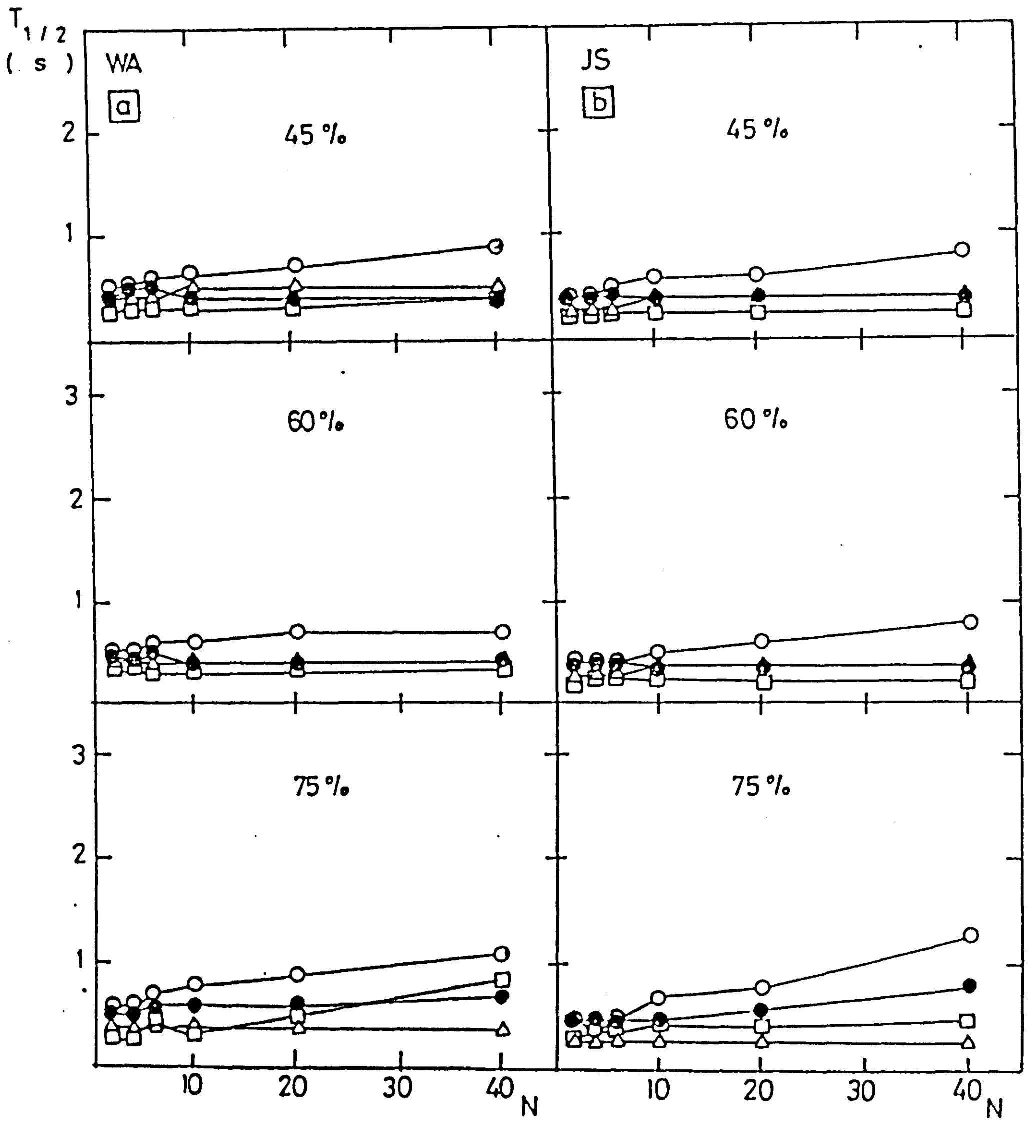

FIG. 4-30. Magnification discrimination for different contrast polarities in the reference field. The square elements were presented on a background of relative luminance 1.0, and the targets were of relative luminance 1.23, with relative magnification denoted on the data plot. The reference elements were of size and relative luminance: 100%, 1.23 and 25%, 1.23 (○); 100%, 1.23 and 25%, 0.77 (●); 100%, 0.77 and 25%, 1.23 (△); 100%, 1.23 (□). Data for two subjects.

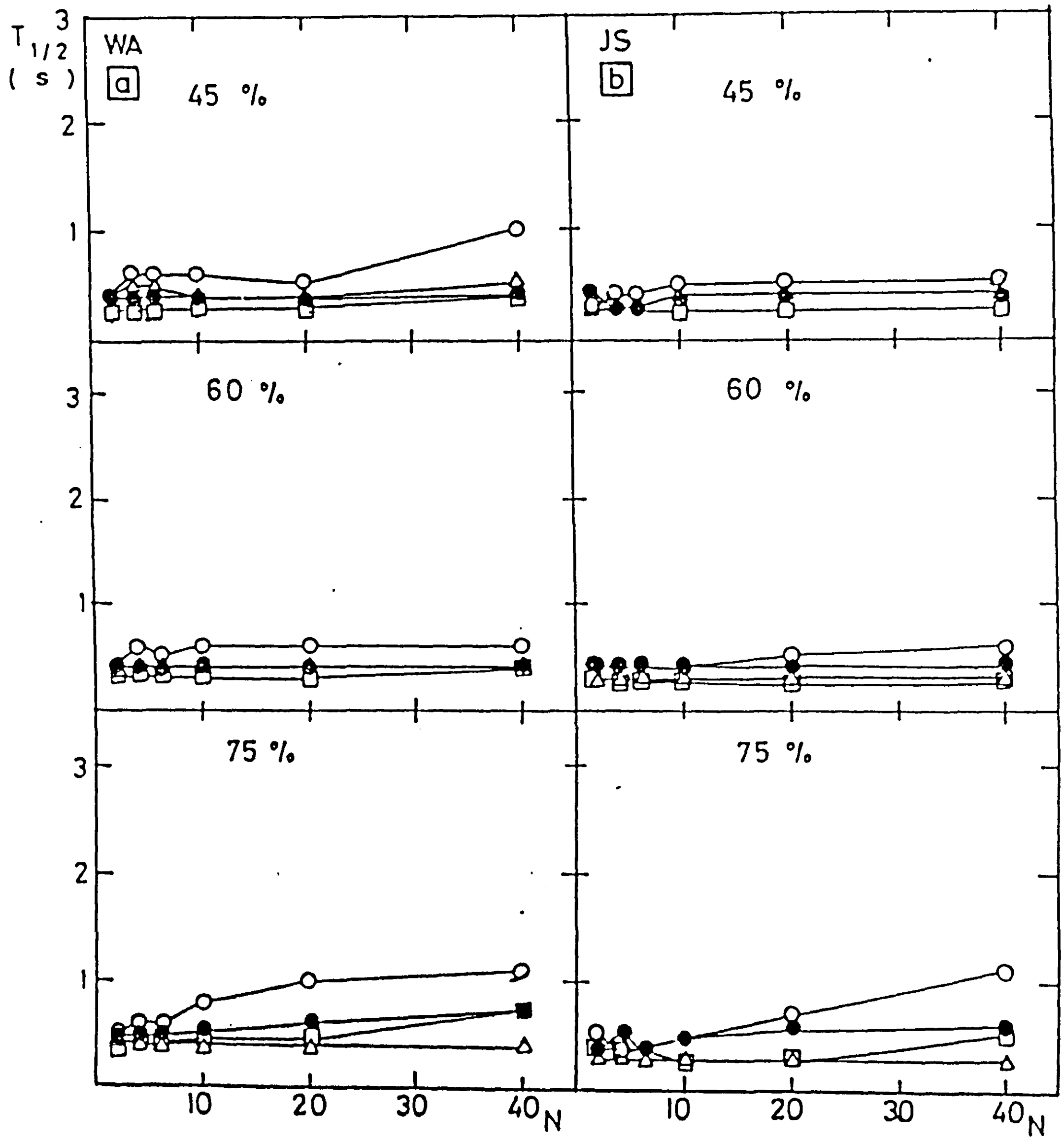

FIG. 4-31. As Figure 4-30, but for targets of negative contrast, with relative luminance 0.77. The reference elements were of size and relative luminance: 100%, 0.77 and 25%, 0.77 (○); 100%, 0.77 and 25%, 1.23 (●); 100%, 1.23 and 25%, 0.77 (△); 100%, 0.77 (□).

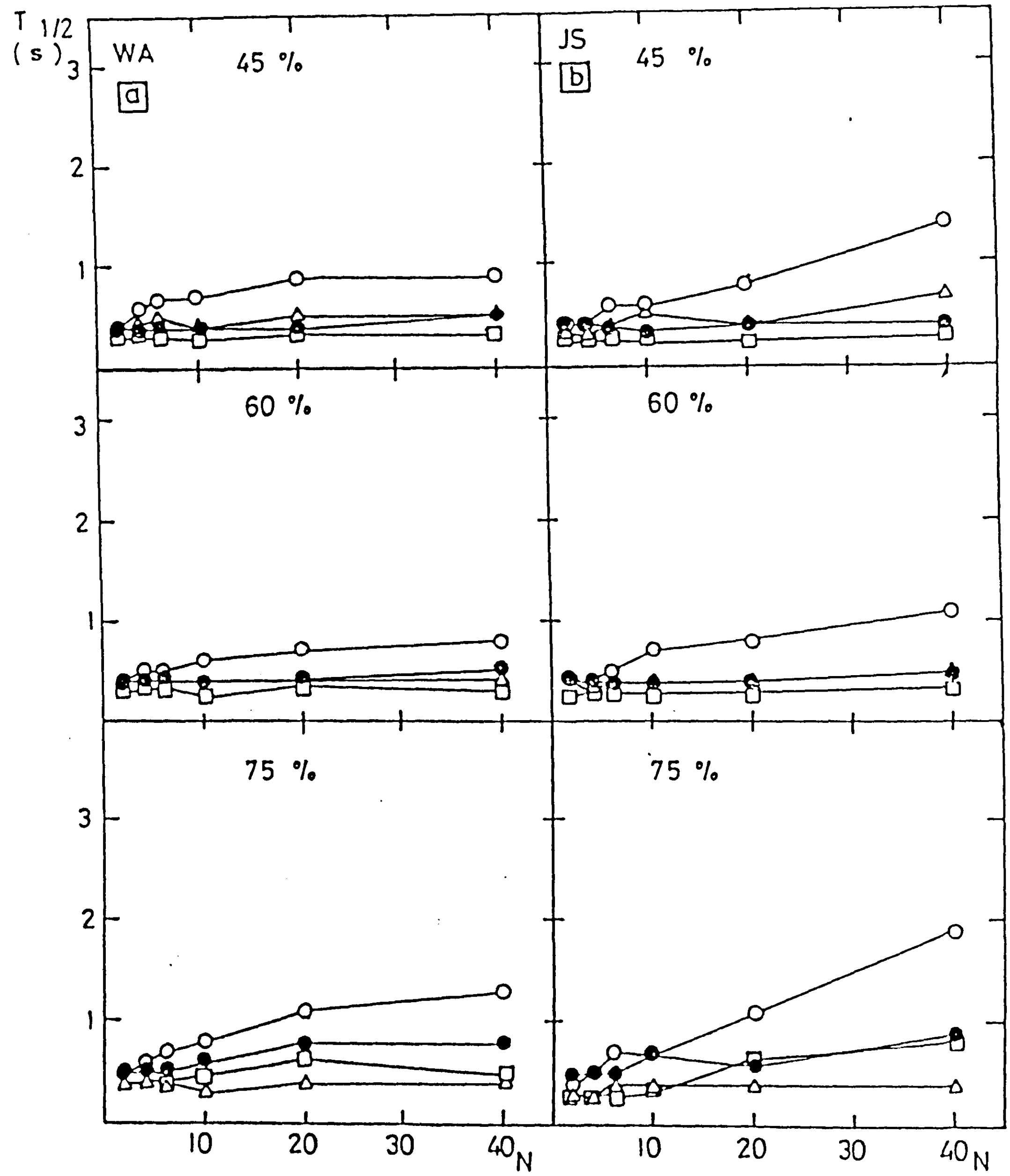

FIG. 4-32. As Figure 4-30, but for higher contrast elements. The targets were of relative luminance 1.43 and the reference elements were of magnification and relative luminance 100%, 1.43 and 25%, 1.43 (○); 100%, 1.43 and 25%, 0.51 (●); 100%, 0.51 and 25%, 1.43 (△); 100%, 1.43 (□). Data for two subjects.

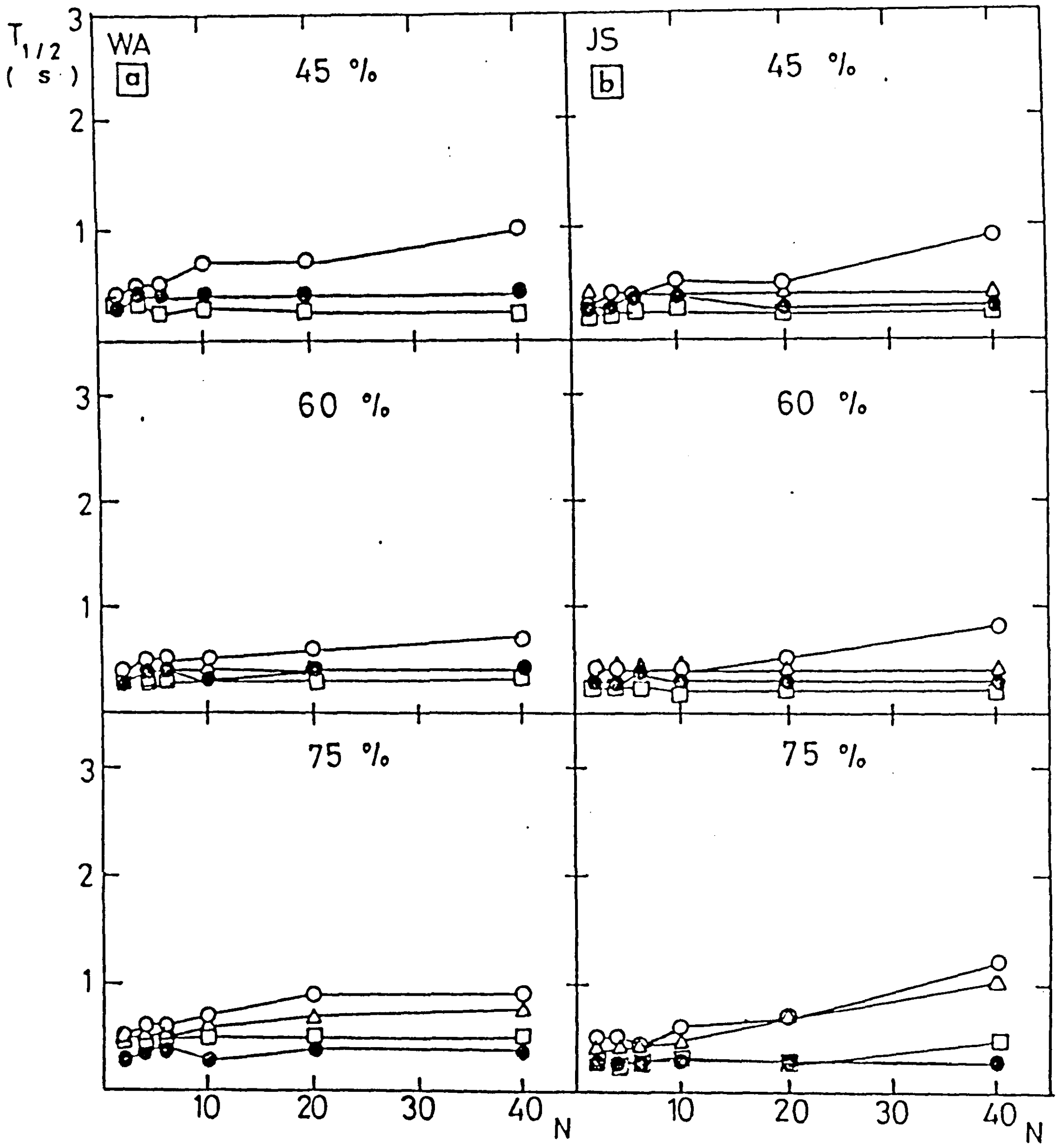

FIG. 4-33. As Figure 4-32, but for targets of negative contrast, with relative luminance 0.51. The reference elements were of magnification and relative luminance: 100%, 0.51 and 25%, 0.51 (◐); 100%, 1.43 and 25%, 0.51 (●); 100%, 0.51 and 25%, 1.43 (△); 100%, 0.51 (□).

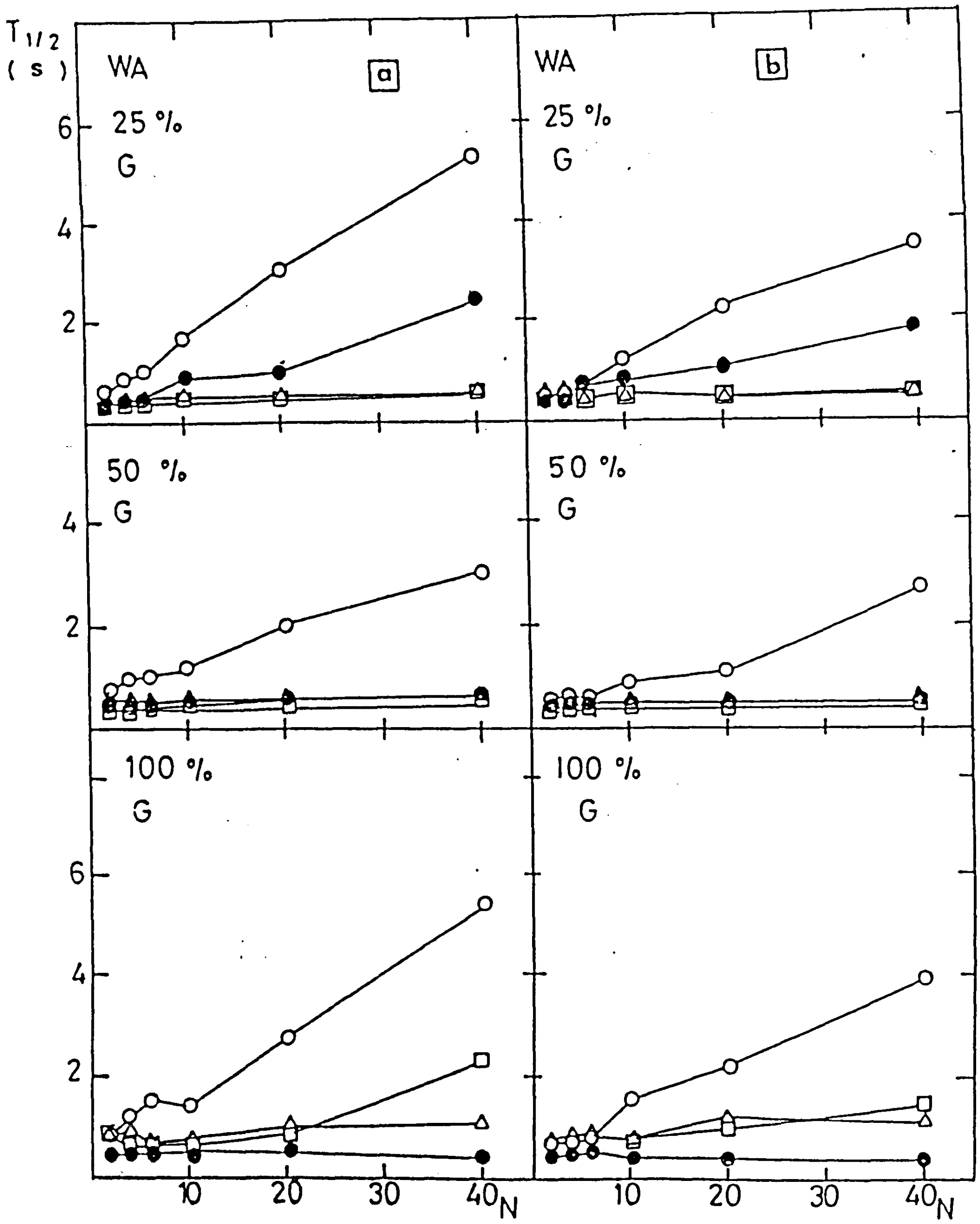

FIG. 4-34. As Figure 4.30, but the magnification of the reference elements were changed to 80% and 31%. (a) Targets of positive contrast, with relative luminance 1.23. The reference elements were of relative size and luminance 80%, 1.23 and 31%, 1.23 (○); 80%, 1.23 and 31%, 0.77 (□); 80%, 0.77 and 31%, 1.23 (●); 80%, 1.23 (△). (b) Targets of negative contrast, with relative luminance 0.77. The reference elements were of relative size and luminance: 80%, 0.77 and 31%, 0.77 (○); 80%, 0.77 and 31%, 1.23 (□); 80%, 1.23 and 31%, 0.77 (●); 80%, 0.77 (△).

discrimination are always much greater than when the reference field consisted of both positive and negative contrasts elements. It is clear that the discrimination process for the all positive or all negative field is non-parallel for all target sizes, while it is parallel for the mixed contrast fields except in one case; for the 25% linear size target it is non-parallel when the mixed contrast reference field's small element (31%) was of the same contrast as the 25% target.

4.6. <u>General Conclusion:</u>

The data presented in this Chapter demonstrate that the visual mechanisms responsible for spatial discrimination with simple geometric patterns are specific in their response to colour and contrast polarity. This is true for both orientation and magnification discrimination, but the results also demonstrate that selectivity is not complete, because discrimination for a mixture of reference elements, of different colours or opposite contrasts, is never as fast as when only one class of element is present in the reference field.

In the case of contrast polarity, psycophysical experiments using adaptation methods have demonstrated that positive and negative contrast components of the retinal image are processed independently. For example, in the case of the "frequency shift effect" (Blakemore et, al., 1970) both Burton et al. (1977) and de Valois (1977) showed that the opponent change in bar-width induced by adaptation to a non-matched grating can be selectively induced for either the positive or, independently, for the negative bars of a test grating. In the case of the "contrast threshold elevation effect" (Gilinsky, 1968; Pantle and Sekuler, 1968;

Blakemore and Campbell, 1969) independent adaptation effects for positive contrast bars was demonstrated by Naghshineh and Ruddock (1978) and subsequently, for both positive and negative contrast bars, by Georgeson and Reddin(1981). Electrophysiological experiments establish separate "on centre" and "off centre" pathways at all levels of the visual system (see Introduction) including retinal bipolar cells (Kaneko, 1970), retinal ganglion cells (Kuffler, 1953), cells of the lateral geniculate nucleus (Hubel and Wiesel, 1961; Wiesel and Hubel, 1966) and those of the striate cortex (Hubel and Wiesel, 1962, 1968). The finding that spatial discriminations are selective for the contrast polarity of the elements is, therefore, consistent with the evidence provided by these cited papers.

In the case of colour, electrophysiology shows clearly that the outputs from the different spatial classes of cone are organised in opponent fashion at all levels of the visual pathways, e.g. retinal horizontal cell (Svaetichin, 1956), retinal ganglion cells (Wagner et al., 1960; de Monasterio, 1978), LGN neurons (Wiesel and Hubel, 1966) and in the striate cortex (Gouras, 1974; Michael, 1978). In general, two chromatic (colour-selective) and a luminance (achromatic) channel are distinguished. The former are usually subdivided into "yellow-blue" and "red-green" opponent responses, and, for example, in the case of retinal ganglion cells, the centre response may be 'red on' with antagonistic surround 'green off', or the converse. Thus colour contrast is encoded in a manner similar to luminance contrast.

Psychophysically a number of phenomena have been attributed to opponent colour effects, and in their pioneering studies Jameson and Hurvich (1955) produced spectral response functions for the opponent mechanisms. Their analysis depended on linear processing of post-receptoral signals, and this has been examined carefully by Larimer et al., (1974, 1975) who found evidence of non-linear processing, particularly in the case of the "yellow-blue" opponent mechanisms. Antagonistic interactions between the red and green photorecptors mechanisms has been demonstrated by Foster and his co-workers (Foster, 1981; Foster et al., 1986) using Stiles' two-colour increment threshold methods (see Introduction).

Direct demonstration of opponent colour spatial responses, based on the inhibitory binocular adaptation described by Ruddock and Wigley (1976) has been given by Hendriks et al., (1982).

Thus, there is considerable evidence for separation of colour information into channels similar to those for "on" and "off" luminance processing, and the data described in this Chapter suggest that differently coloured elements have separate representations. There is, however, a suggestion that spatial and chromatic signals are processed separately, in different areas of the pre-striate cortex (Zeki, 1978). Direct experiments with equiluminance chromatic patterns, however, have demonstrated that these simple geometrical shapes can be discriminated on the basis of colour alone (Javadnia and Ruddock, 1988b).

The data obtained with bars and edges of different contrast, which were designed to correspond to the stimuli used in the electrophysical study of cortical neurons, failed to provide such clear evidence of contrast specific responses.

CHAPTER FIVE

Chapter Five

Discrimination with a Reference Field of Mixed Orientation and Magnification

5.1. Introduction:

The experiments described in Chapters Three and Four covered the discrimination of target orientation or magnification with a complex reference field of either mixed orientation or magnification respectively, that is, the two spatial parameters were kept strictly separate. In this Chapter, I examine whether these two parameters interfere. Therefore, the reference field contained two classes of element which differed both in size and orientation. The target had one parameter (e.g. orientation) in common with one class of reference element, but differed from it in the other.

In other, preliminary experiments, the two classes of reference element used for the measurement of orientation discrimination differed only in magnification, and for measurement of magnification discrimination, they differed only in orientation. The results of these preliminary experiments are presented in two groups, the first of which describes the effect of changing the orientation of the target and the second the effects of changing the magnification.

The possible choices for these combination of mixtures are great, and a choice was made of those which gave reasonable results with lines, triangles and squares.

5.2. Patterns and Experiments:

The stimuli used in this Chapter are illustrated in Chapter Two (Fig 2-10). These patterns were used to construct the reference field and were presented on a black background. The reference elements and the targets were all of greenish colour, given by a combination of blue (relative luminance 0.17) and green (relative luminance 0.54). The results for each shape, lines, triangles and squares are presented separately.

5.3. Subjects:

Three postgraduate students participated in these experiments: W.A., female; A.M., male and J.S., female.

5.4. Results:

As I mentioned earlier the results are divided into two sections, for orientation discrimination and magnification discrimination.

5.4.1. Discrimination of Target Orientation:

(i) Lines:

The first group of experiments were performed with the reference field consisting of lines with two relative lengths, 100% and 50%, oriented vertically. The target length in most of the experiments was 100% and targets differed in orientation from both classes of the reference element.

Data for targets (100%) length, oriented at 11 deg., 45 deg. and 78 deg., are presented in Fig

5-1a for the mixed reference field, and for two simple reference fields consisting of either class of reference element. It is clear from the graph that $T_{\frac{1}{2}}$ values for the mixed field are very similar to those obtained with the simple reference elements, and remain essentially independent of the number of reference element N, i.e. the targets are discriminated in parallel. Similar results were also obtained when using the same reference field but with the targets oriented at 11 deg., 22 deg. and 31 deg. (Fig 5-1b), or at 15 deg., 30 deg. and 45 deg. (Fig 5-2a).

A smaller target (50%) was used with the same reference elements, and results for targets oriented at 9 deg., 24 deg. and 36 deg. are given in Fig 5-2b. The $T_{\frac{1}{2}}$ values for the 9 deg. with the mixed reference field were in this case a little higher than those for both of the simple reference field, but are still unaffected by the increase in N, i.e. it is considered parallel processing.

The results of this section indicate that simply introducing different target lengths into the reference elements does not influence discrimination of line orientation, thus at the simplest level, orientation and magnification are independent variables.

(ii) <u>Triangles:</u>

The first experiments were performed using two sizes of equilateral triangle, 100% and 50% length size, both oriented upright, as the reference elements. The target length was 50% set at various

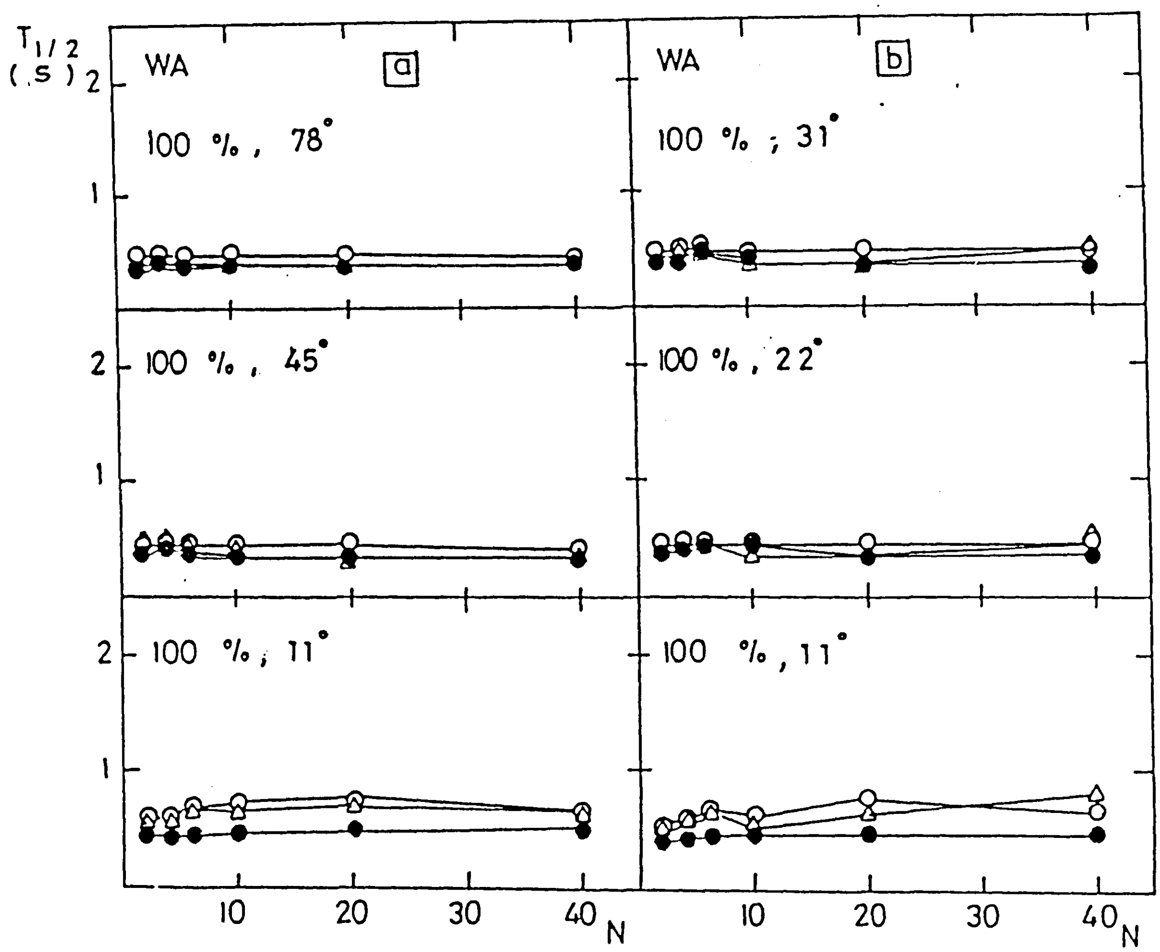

FIG. 5_1. Orientation discrimination with line elements of mixed orientation and magnification. Targets are of 100% relative size and orientations as specified on each plot. The reference elements were oriented upright and of size: 100% and 50% (○); 50% (●); 100% (△).

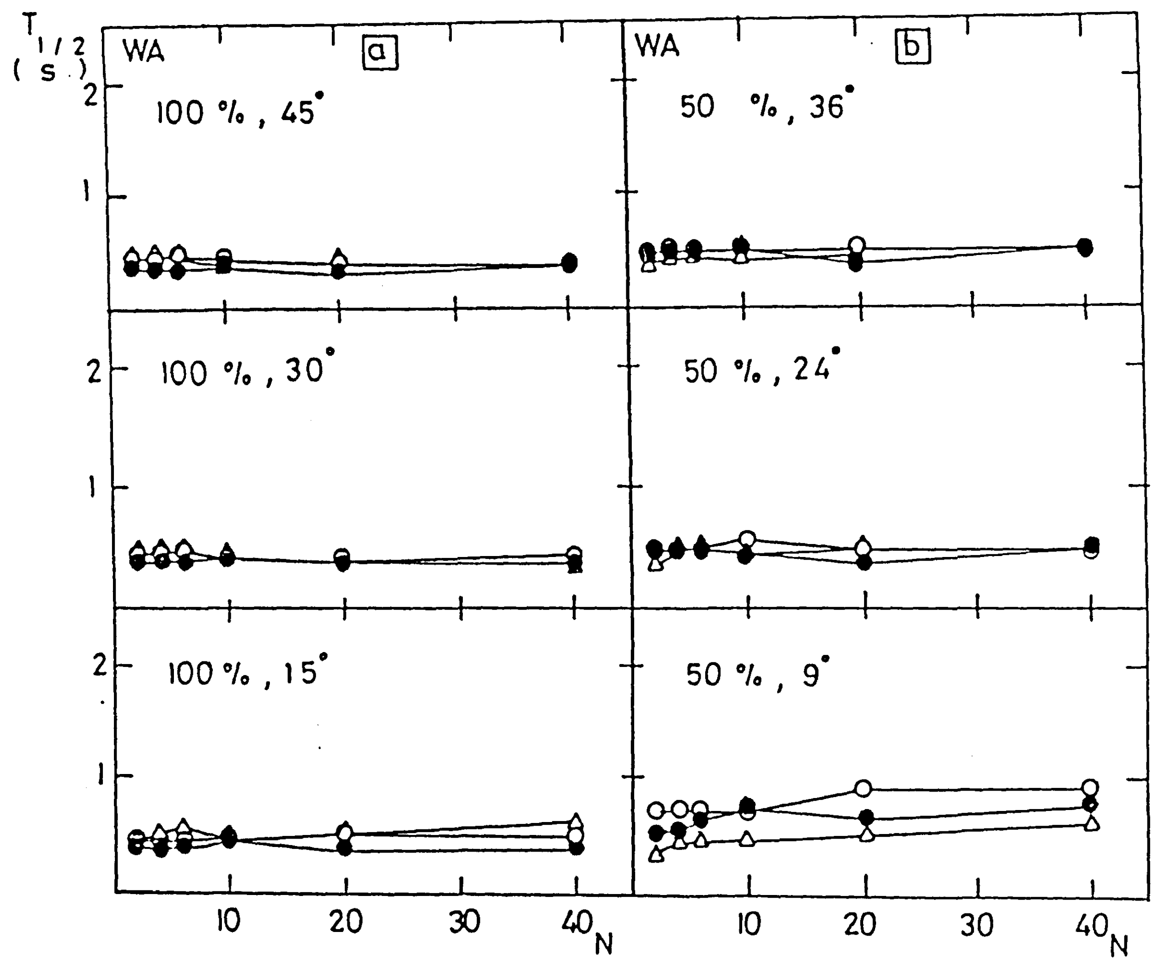

FIG. 5_2. Orientation discrimination with line elements of mixed orientation and magnification. The targets were of 100% relative size and orientation as specified on the plots. The reference elements were oriented upright and of relative size: 100% and 50% (O); 50% (●) and 100% (Δ).

orientations (Fig 5-3). The results presented in Fig 5-3 refer to two sets of target orientations, one with large variations in orientation from the reference elements (30, 60 and 90 deg.) and the other with smaller steps of rotation (10, 20 and 30 deg.). The two graphs give similar results. $T_{\frac{1}{2}}$ values are independent of N for the simple reference elements, and there is a slight increase in $T_{\frac{1}{2}}$ for the mixed reference field, except with the 10 deg. target. In that case, $T_{\frac{1}{2}}$ values increase somewhat with the mixed reference field and with one of the simple reference fields (composed of the smaller reference elements).

Similar experiments were performed with large (100% length) targets, and two sets of target orientations were examined (30, 60, 90 deg. or 12, 18 and 30 deg.). The results, presented in Fig 5-4, show that $T_{\frac{1}{2}}$ values are independent of N for the mixed as well as for the simple reference fields. Overall, the results of these experiments show that introducing elements larger than the target into the mixed reference field interferes slightly with discrimination causing an increase in the $T_{\frac{1}{2}}$ values (Fig 5-3), whereas introducing elements smaller than the target into the mixed reference field has no effect on $T_{\frac{1}{2}}$ values (Fig 5-4).

A more precise examination of the effect of the size of the elements on orientation discrimination was obtained by using mixed reference fields, in which both the size and orientation of the two classes of elements differed from each other. The combination used was 100%, upright orientation, and 50%, 30 deg. orientation, and comparison data

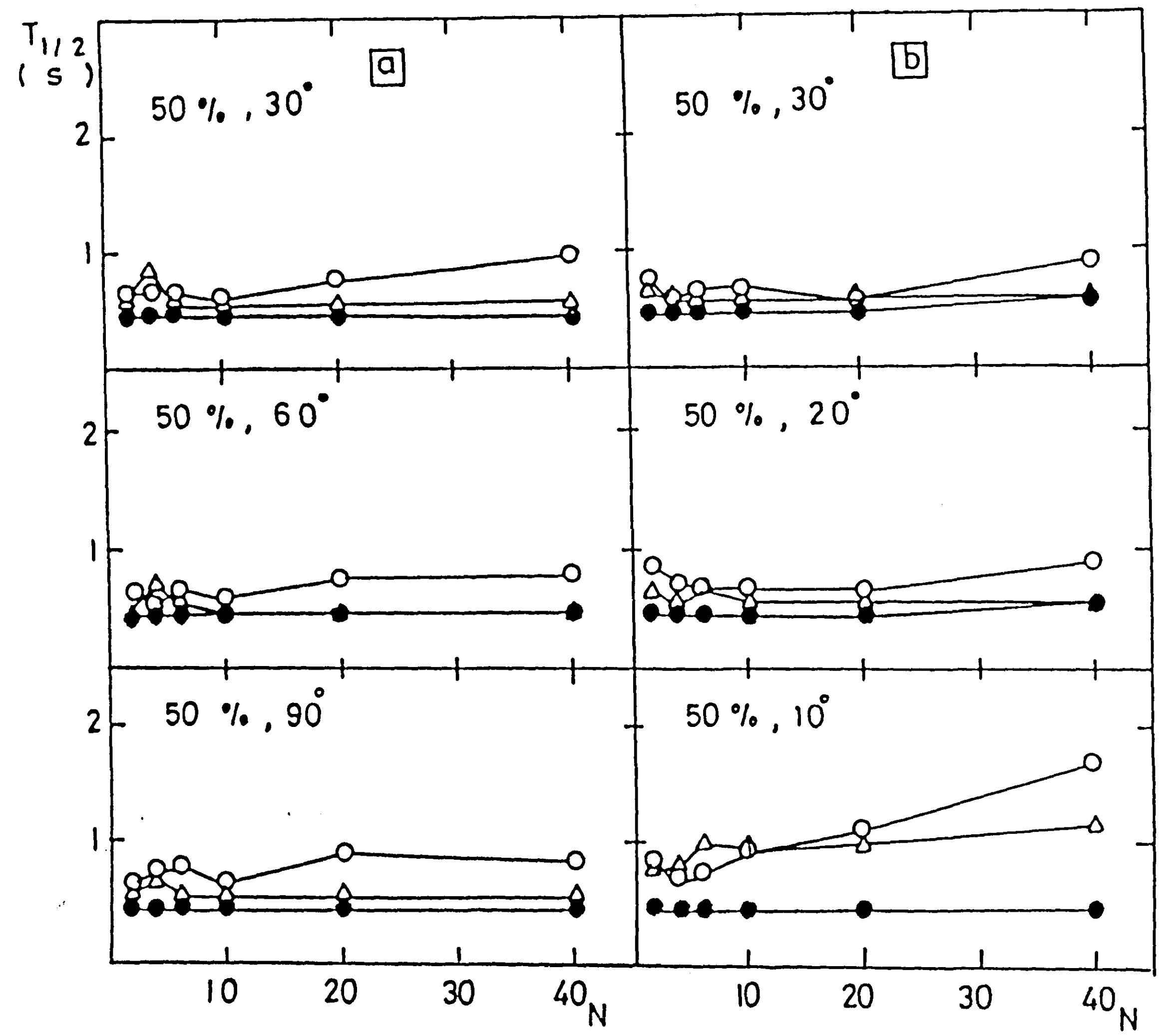

FIG. 5.3 . Orientation measurements with triangular elements of mixed orientation and magnification. The targets were of 50% relative size and orientation as marked on the plot. The reference elements were oriented upright (i.e. ▲) and were of size 100% and 50% (○); 100% (●) and 50% (△).

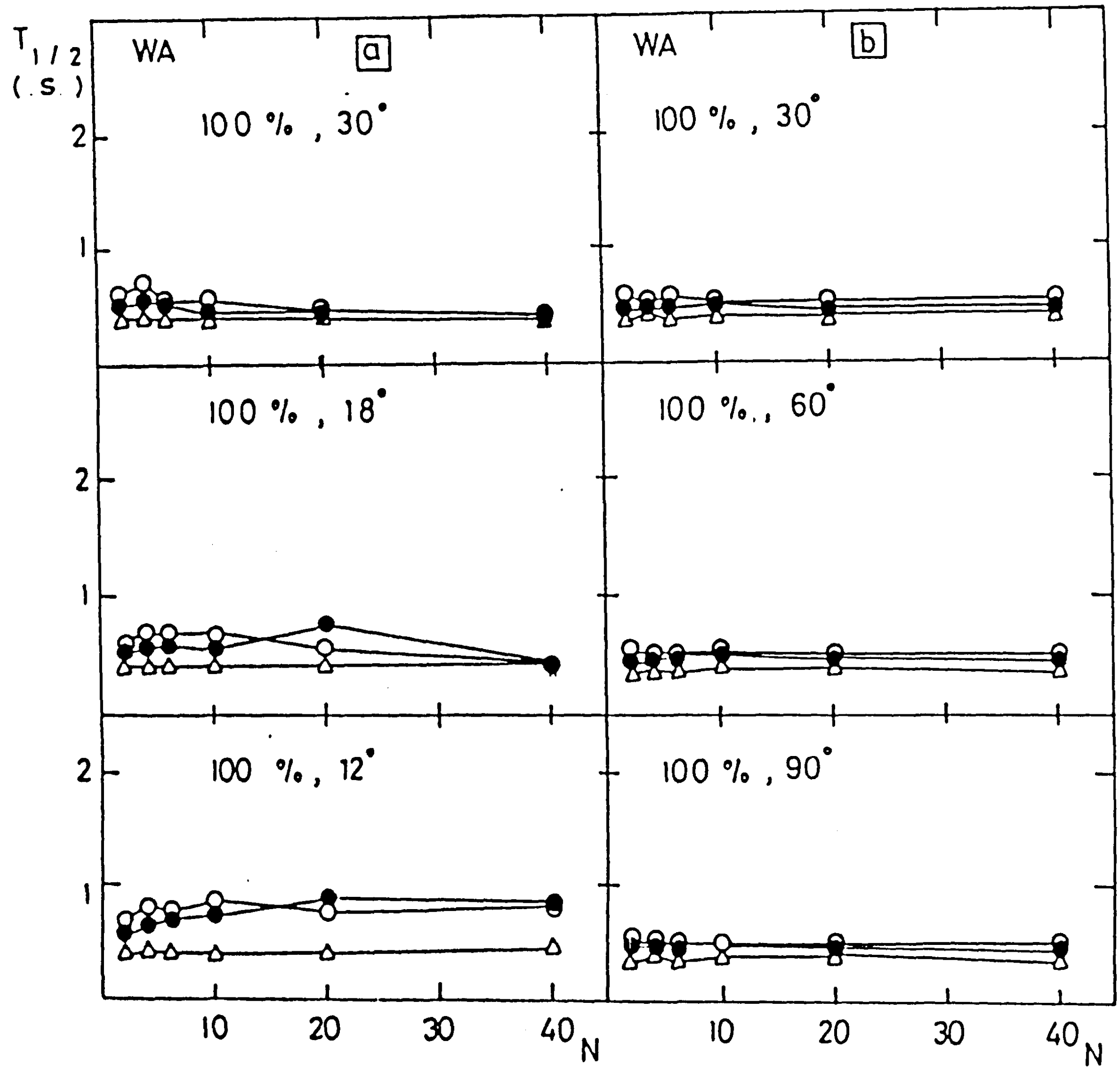

FIG. 5-4 a,b: Orientation discrimination with mixed orientation and magnification for triangular elements. The targets are of relative size of 100% and orientation specified on the plots. The reference elements were oriented upright (▲) and were of relative size: 100% and 50% (○); 100% (●) and 50% (△).

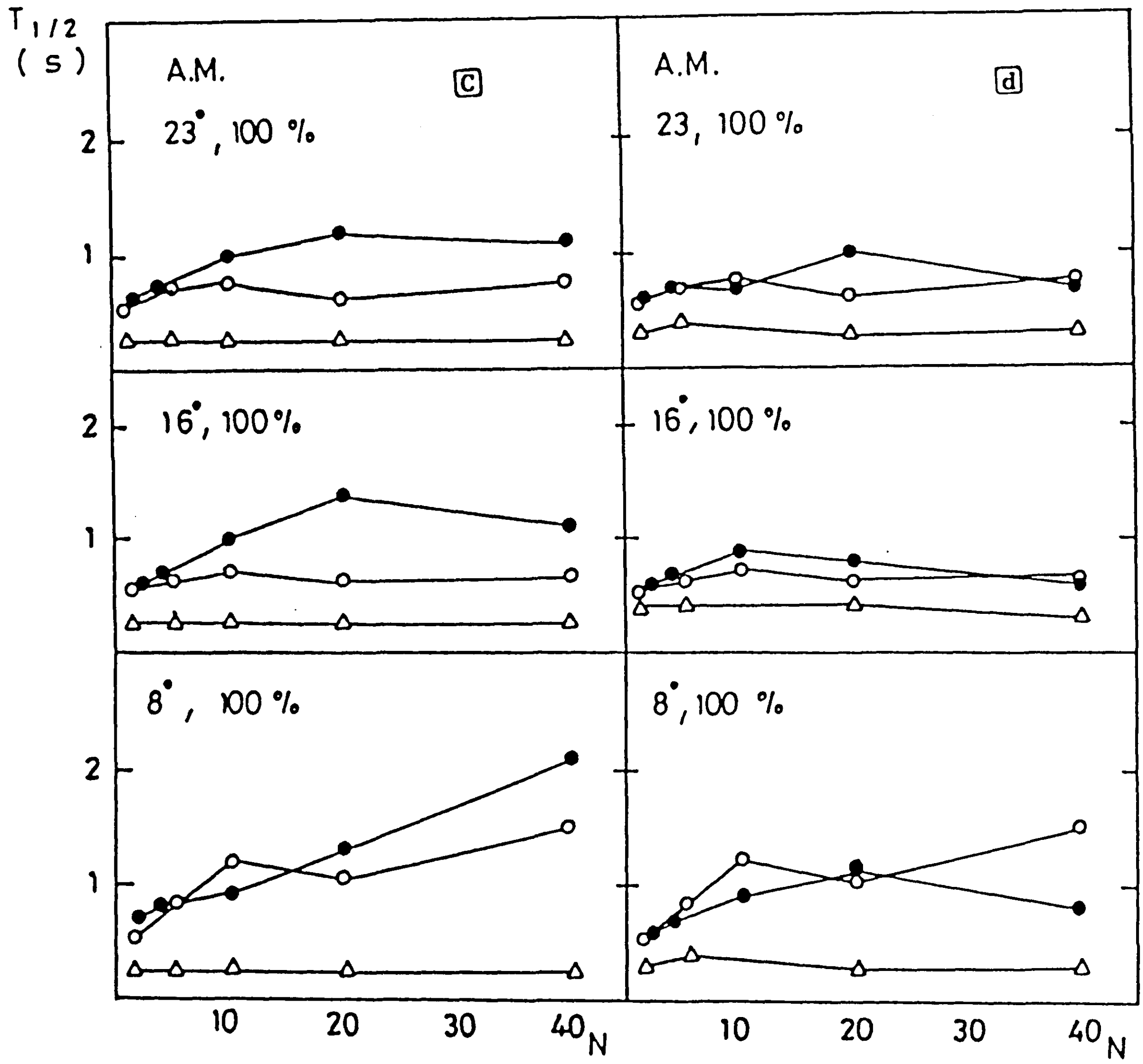

FIG. 5_4 c,d: Similar to Figure 5-4 a,b, but for reference elements of orientation and size as follows:

(c) Pointing upward, 100% and 30°, 30% (●); 30°, 30% (Δ); and pointing upward, 100% (o).

(d) All pointing upward: 100% and 30%, (●); 100%, (O) and 30%, (Δ).

were obtained with the same mixture of orientations, both 50% size, and with a simple, 50%, 30 deg. orientation reference field and with a simple 50%, upright reference field. The target size was 50%, oriented at 6 deg., 11 deg. or 18 deg. The results, illustrated in Fig 5-5 show that $T_{\frac{1}{2}}$ values vary greatly, with the choice of reference field. For the mixed reference field where both classes of elements matched the target in size, $T_{\frac{1}{2}}$ increases very rapidly with N and even for the 50%, 30 deg. simple reference field, $T_{\frac{1}{2}}$ increases with N, although less sharply than with the mixed 50% field. With the mixed reference field containing both sizes of element, however, the $T_{\frac{1}{2}}$ values are lower than those for the field containing 50% elements at 0 deg. and 30 deg. orientations, but the results for the two subjects are rather different from each other. For subject JS, $T_{\frac{1}{2}}$ values for the reference field with elements of mixed orientation and size are either similar to (6 deg. target) or less than (11 deg. and 18 deg. target) those for the simple 50%, 30 deg. field. For subject WA, however, $T_{\frac{1}{2}}$ values for the mixed reference field are greater than those for the simple field for the 6 deg. and 11 deg. targets and are less than them only for the 18 deg. target. None-the-less, the results indicate that the effect of the reference elements is dependent on their magnification and if they differ in size from the target, their influence on discrimination is reduced.

In order to examine in detail the effect on orientation discrimination of element size, the size of one class of reference element in the mixed field was varied systematically. This was

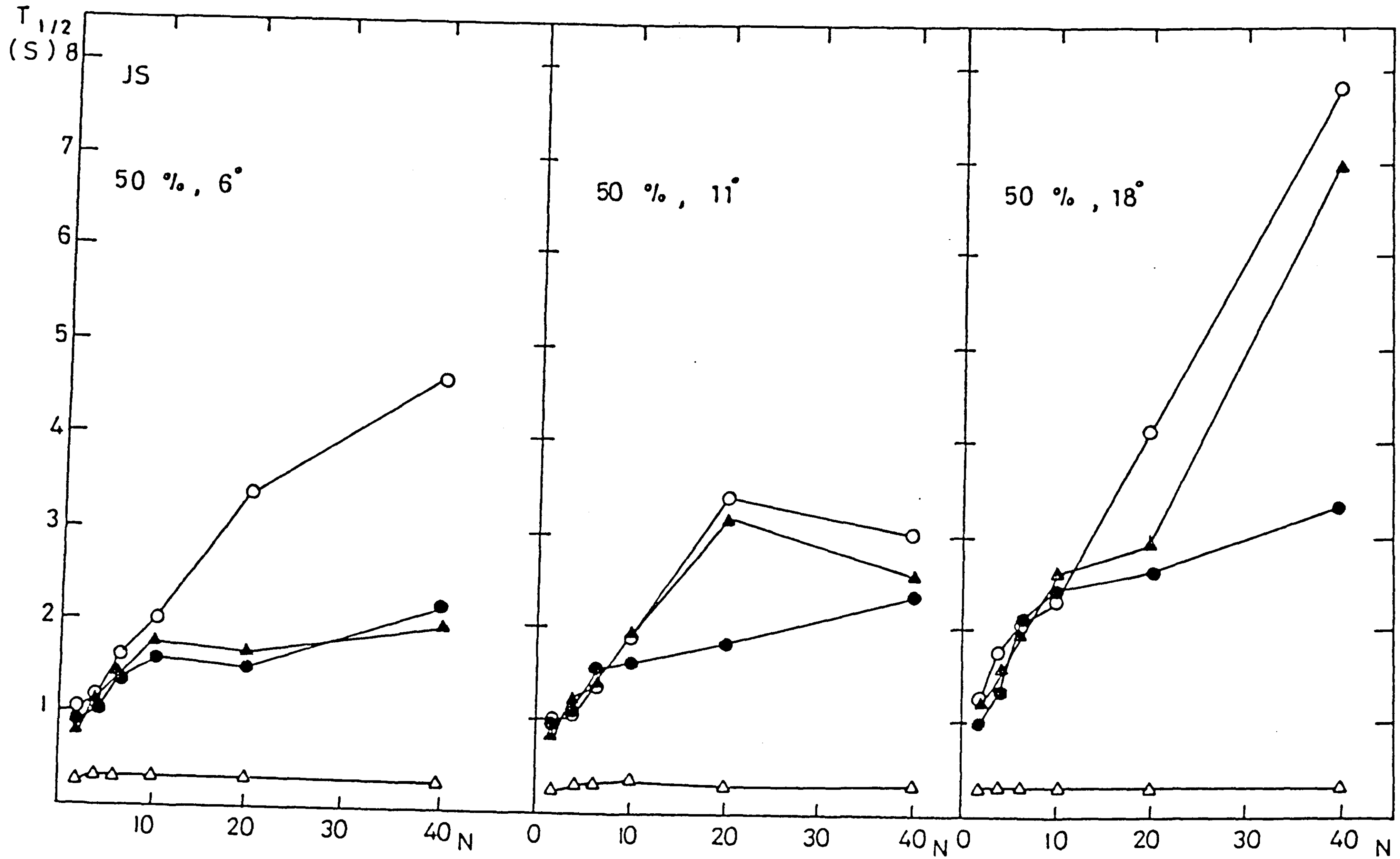

FIG. 5_5a. Orientation discrimination for triangles of mixed magnification and orientation. The targets were of relative size and orientation specified on the plots. The reference elements size and orientation were: 50%, 0° and 50% 30° (O); 100%, 0° and 50%, 30° (●); 50%, 30° (▲); and 100%, 0° (Δ). for subject JS

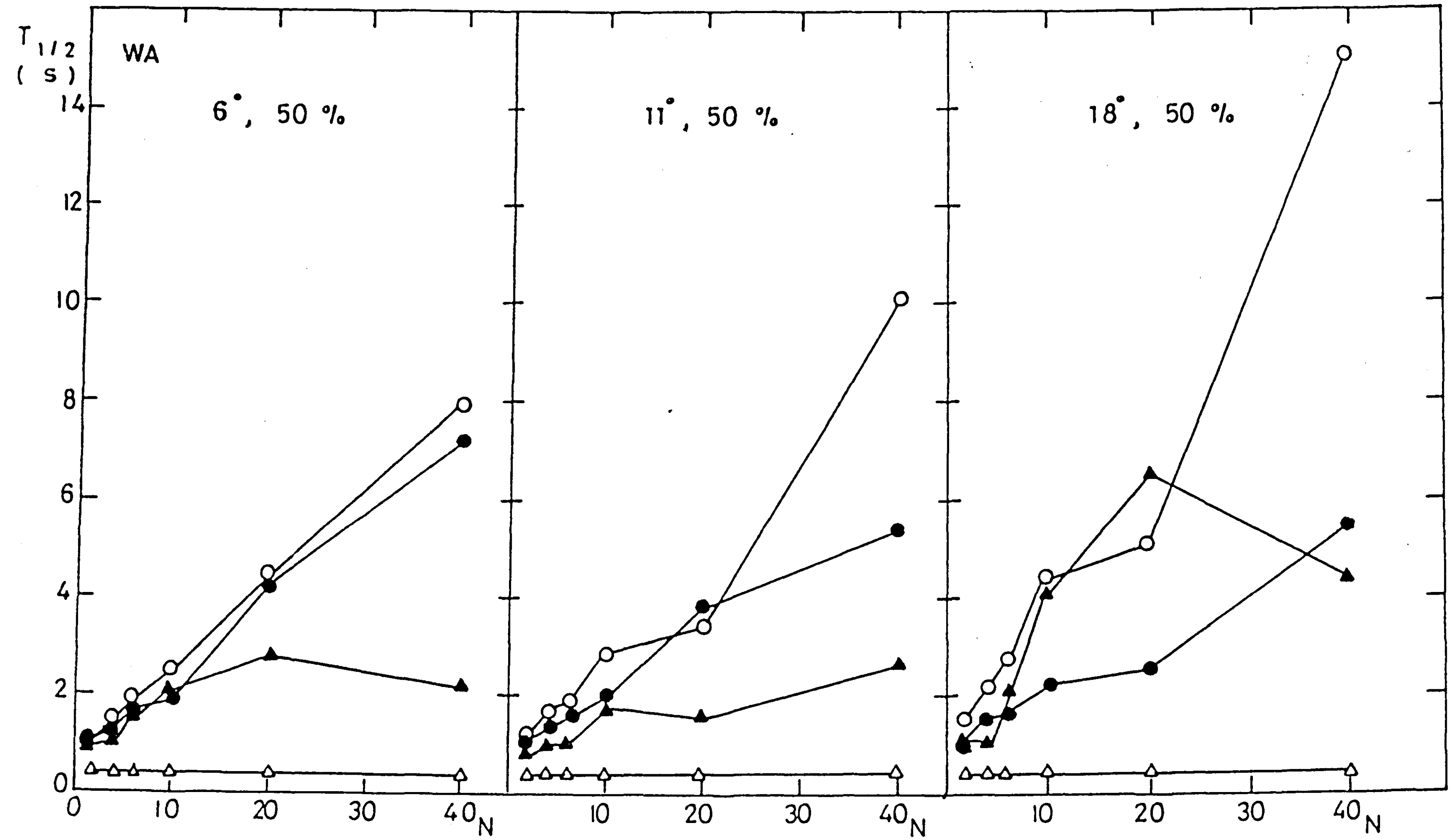

FIG. 5_5b: As Fig. 5.5a, but for subject WA.

performed by using for one reference class an upright triangle with 80% side length, and for the other a triangle varying in size and oriented at 30 deg., set at a series of different side lengths, namely, 100%, 90%, 80%, 70% and 60%. The target size was 80%, matching the size of the fixed class of reference element, and it was set at 7 deg., 10 deg. or 17 deg. relative orientation. The data obtained (Fig 5-6) show that as the size of the second class of reference element moves away from the size of the target, $T_{\frac{1}{2}}$ values tend to go down. This demonstrates that as the difference in magnification between the target and the variable class of reference element increases, the effect of the latter on orientation discrimination is reduced. Thus, there is a tuning range of magnification to which the orientation selective mechanism is sensitive.

This last conclusion is demonstrated by plotting the $T_{\frac{1}{2}}$ values for the 40 reference elements against linear size of the variable reference element (Fig 5-7). For each target orientation, response is maximum around the 80% magnification, which correspond to the target size. These results again demonstrate that the mechanism which mediates orientation is tuned for the size of the patterns, because the interaction between the two reference orientations described in Chapter Three, is reduced when the two classes of reference element are not matched in size.

(iii) <u>Squares:</u>

Similar measurements were performed using square shape elements to study the discrimination of

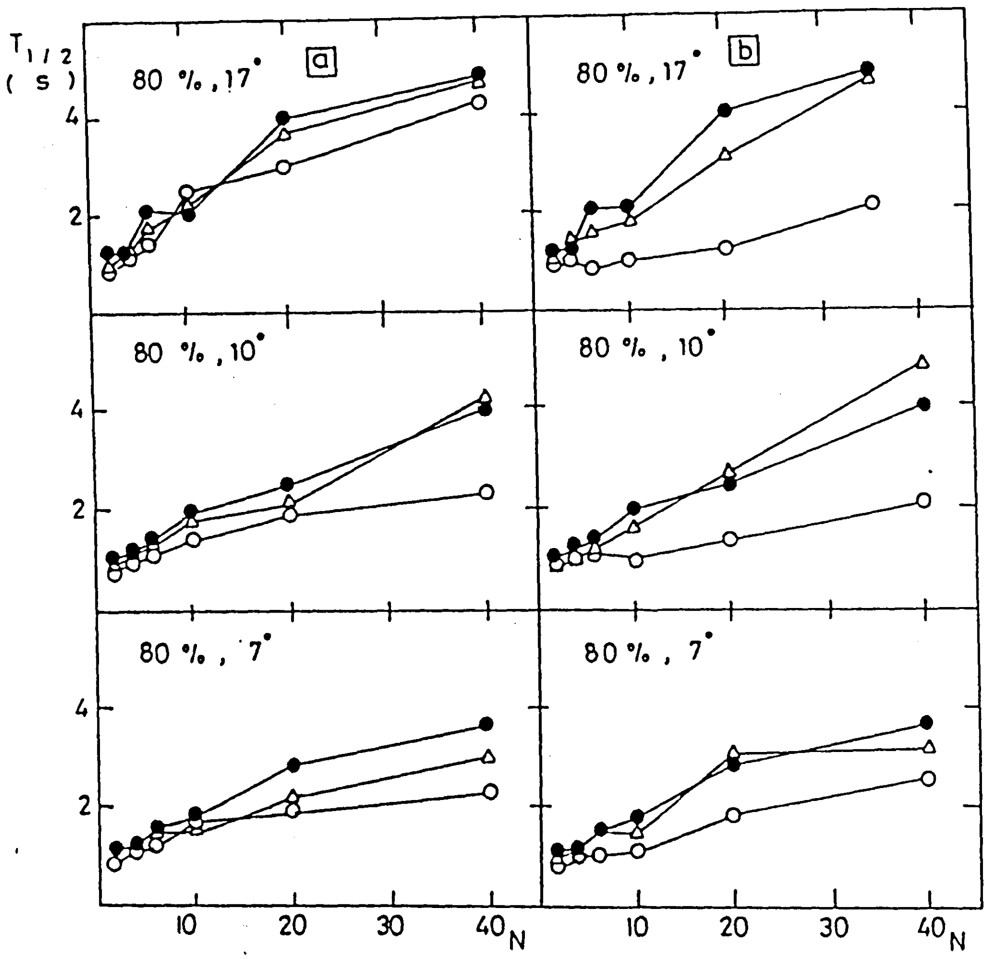

FIG. 5 _ 6 . Orientation discrimination with triangluar elements of mixed orientation and magnification. The targets used were of size 80% and orientation specified on the plots. (a) The reference elements were of size and orientation: 80%, 0° and 100%, 30° (O); 80%, 0° and 90%, 30° (Δ); and 80%, 0° and 80%, 30° (●). (b) The reference elements were of size and orientation: 80%, 0° and 60%, 30° (O); 80%, 0° and 70%, 30° (Δ); and 80%, 0° and 80%, 30° (●).

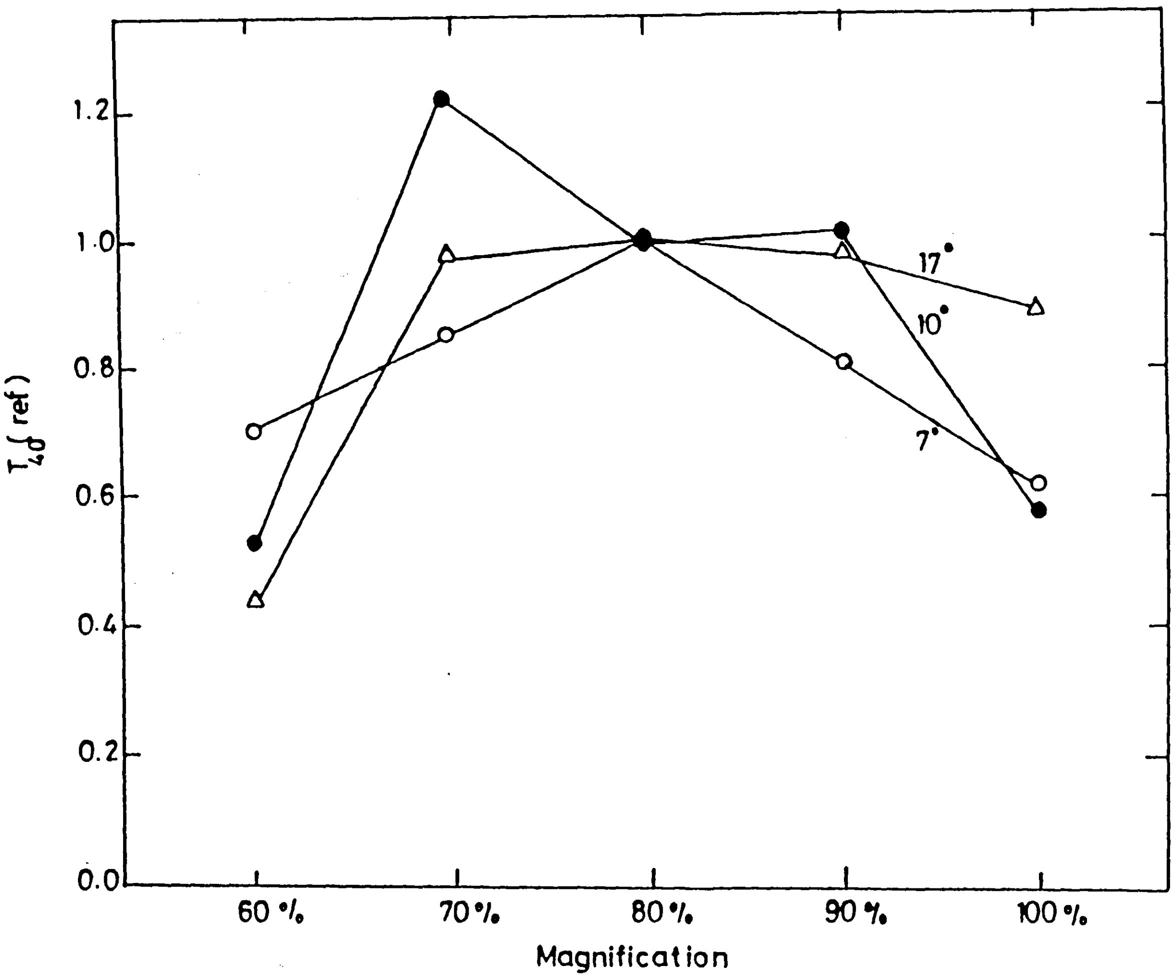

FIG. 5-7. Orientation discrimination data taken from Figure 5-6. The $T_{\frac{1}{2}}$ values are for N=40 normalized for the 80%, magnification is plotted against the magnification of the variable reference element.

target orientation from a reference field consisting of two classes which differ in size.

Preliminary data were obtained with a reference field consisting of two classes of element both upright in orientation, and of relative size 100% and 50%. The target matched the size of the larger reference elements in one set of measurements and that of the smaller reference elements in the other. The results are presented in Fig 5-8 for orientations of 15 deg., 25 deg. and 45 deg. for the large target and of 14 deg., 29 deg. and 45 deg. for the small target. The $T_{\frac{1}{2}}$ values for all target discriminations were independent of N except for one case, that with the small target at 14 deg. orientation, in which there is a slight increase in $T_{\frac{1}{2}}$ with N. In this case however, the simple reference field consisting of the smaller reference squares gives a similar increase in $T_{\frac{1}{2}}$ values and addition of the larger reference element has only a small effect. Like the corresponding experiments with triangles, these results indicate that orientation and magnification are effectively independent parameters in determining orientation discrimination.

As with the triangular elements, further measurements were made in which two classes of reference element differed in both orientation and magnification. One of the two was 80% magnification oriented at 45 deg. from the upright and the other 30% magnification, oriented upright. The target size was 80%, and was oriented at 8 deg., 16 deg. and 28 deg. Comparison data are given for the same mixture of reference fields but

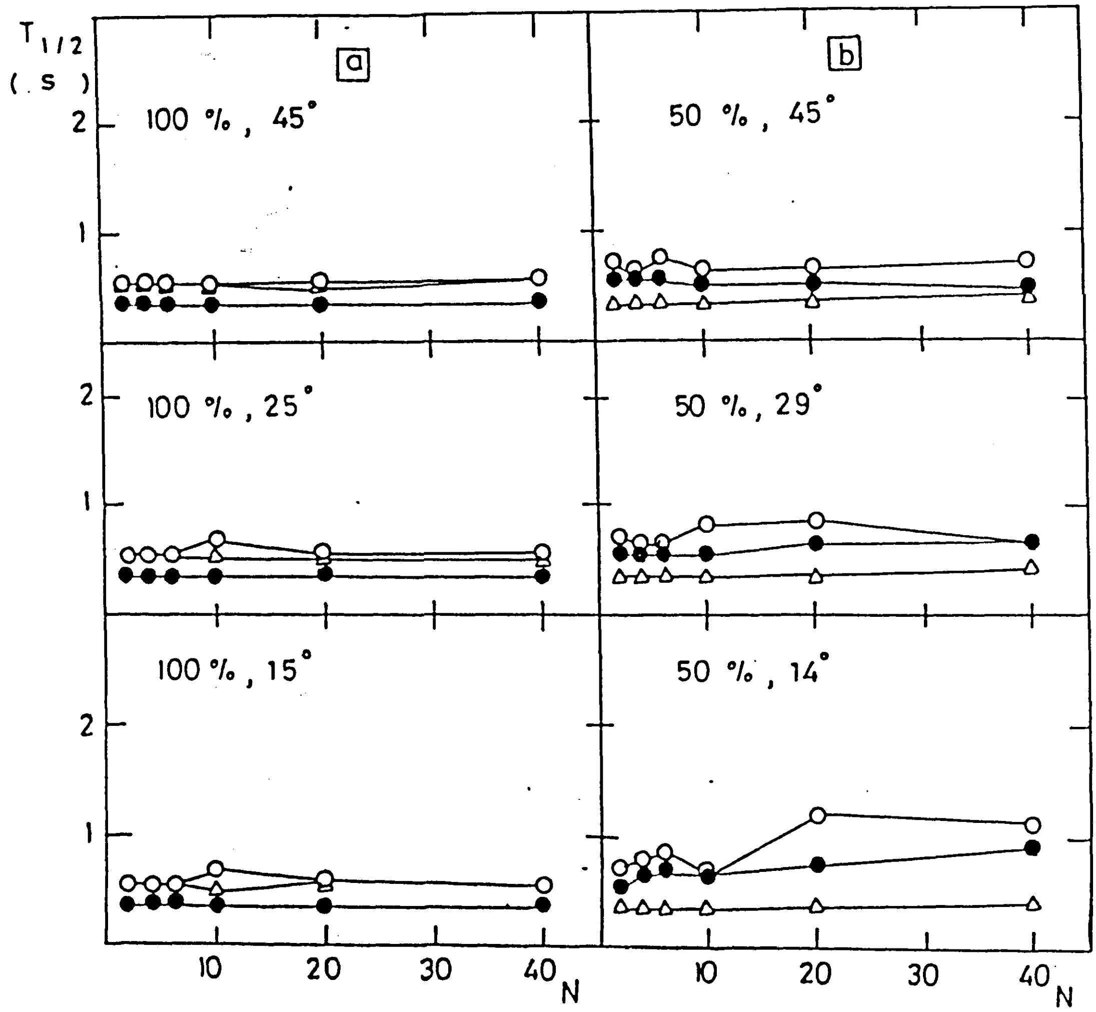

FIG. 5 _ 8 . Orientation discrimination with mixed orientation and magnification for square elements. The target sizes and orientations are marked on the plots. The reference elements were oriented upright (■) and were of size: 100% and 50% (O); 100% (Δ); and 50% (●).

with both reference elements at 80% size, and for a reference field containing only 80%, 45 deg. elements. In this case, the results show clearly (Fig 5-9) that the mixed field in which the reference elements differ in size is equivalent to the simple field containing only the 80% elements, $T_{\frac{1}{2}}$ being essentially independent of N for both classes of fields. For the mixed reference fields consisting of both orientations at 80% size, however, $T_{\frac{1}{2}}$ values increase significantly as N increases. In these measurements, the effect of changing the size of the reference elements is particularly clear; when the reference elements differ in size, they act as if only the 80% elements, which match the target, are present.

In order to quantify this further, measurements were made for a series of mixed fields in which one of the two reference elements was changed in size relative to the other, which always matched the target. Results are given in Fig 5-10a&b and show that as the size difference between the two reference elements increases, so the $T_{\frac{1}{2}}$ values become smaller. Similarly, as with the triangles, by plotting $T_{\frac{1}{2}}$ values for N=40 against the linear size of the variable reference element, for each of the target orientations (Fig 5-10c&d), it is clear that, with one exception, $T_{\frac{1}{2}}$ values are maximum where the reference elements all match the target. This result demonstrates, as for triangles, that the mechanism which mediates discrimination of orientation is tuned to the size of the pattern.

5.4.2. Discrimination of Target Magnification:

The orientation selectivity of mechanisms which mediate

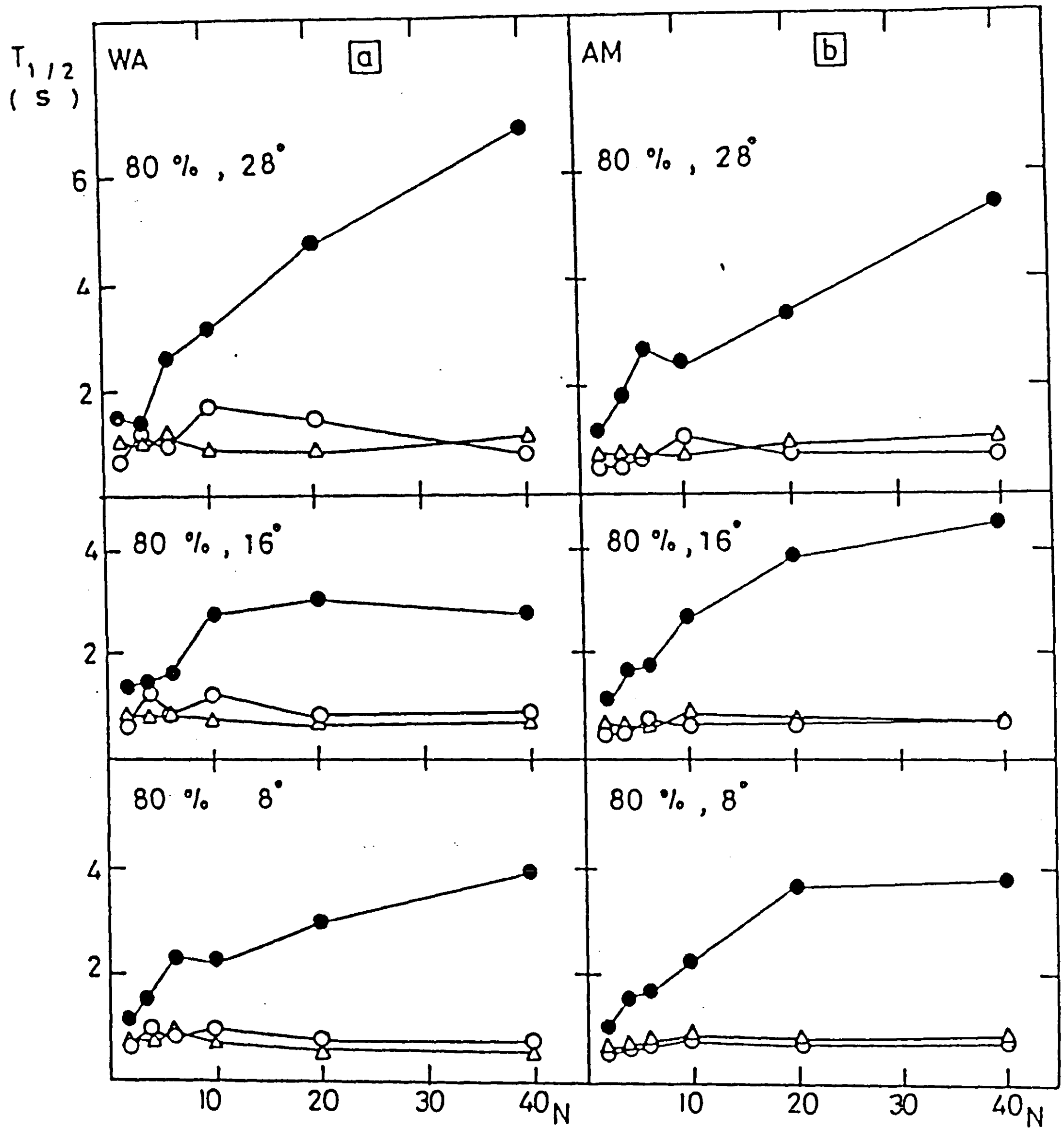

FIG. 5_9. Orientation discrimination for square elements of mixed orientation and magnification. The targets were of size 80% and of orientation specified on the plots. The reference elements were ◆ 80% and ■ 30% (O); ◆ 80% and ■ 80% (●); ◆ 80% (Δ). Data are for two subjects.

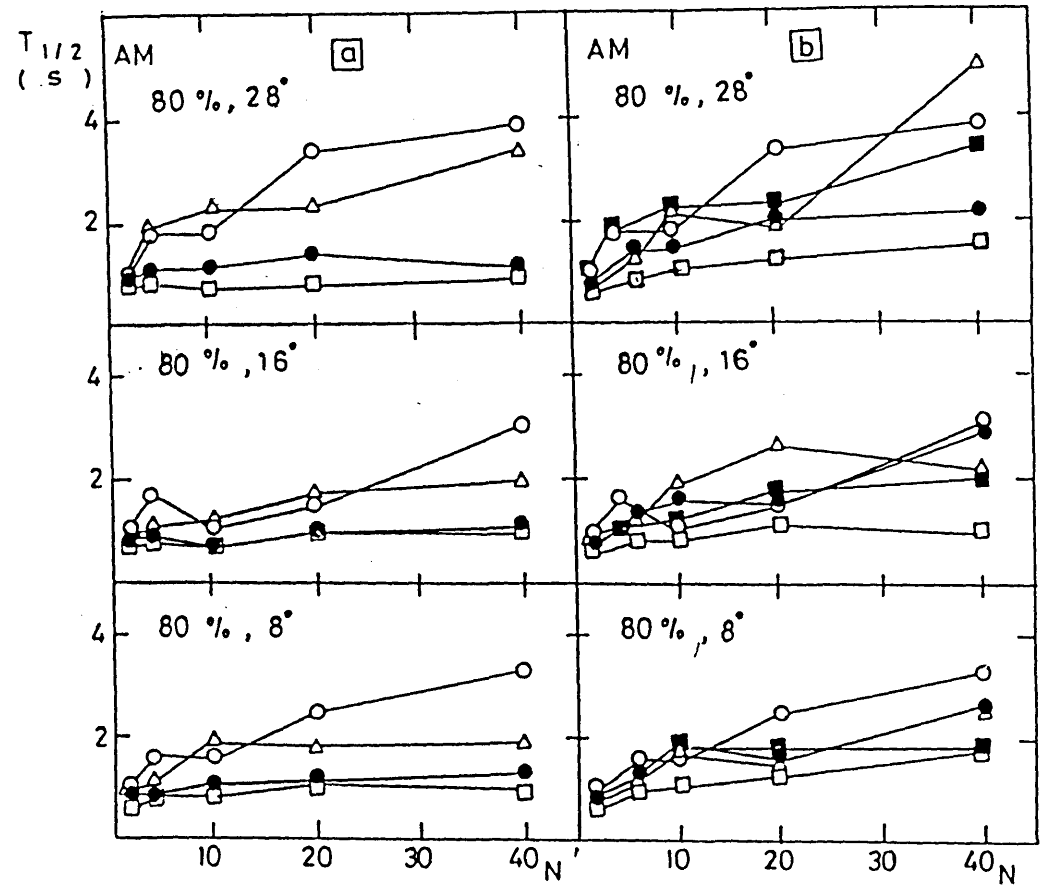

FIG. 5 _ 10-a,b: Orientation discrimination for squares of mixed orientation and magnifications. The target size was 80% and orientation is specified on each plot. (a) Reference fields ■ 80% and ◆ 90% (△); ■ 80% and ◆ 80% (○); ■ 80% and ◆ 70% (●); 80% ■ and ◆ 60% (□). (b) Reference fields: ■ 100% and ◆ 80% (△); ■ 80% and ◆ 80% (○); ■ 70% and ◆ 80% (●); ■ 60% and ◆ 80% (□); ■ 30% and ◆ 80% (■).

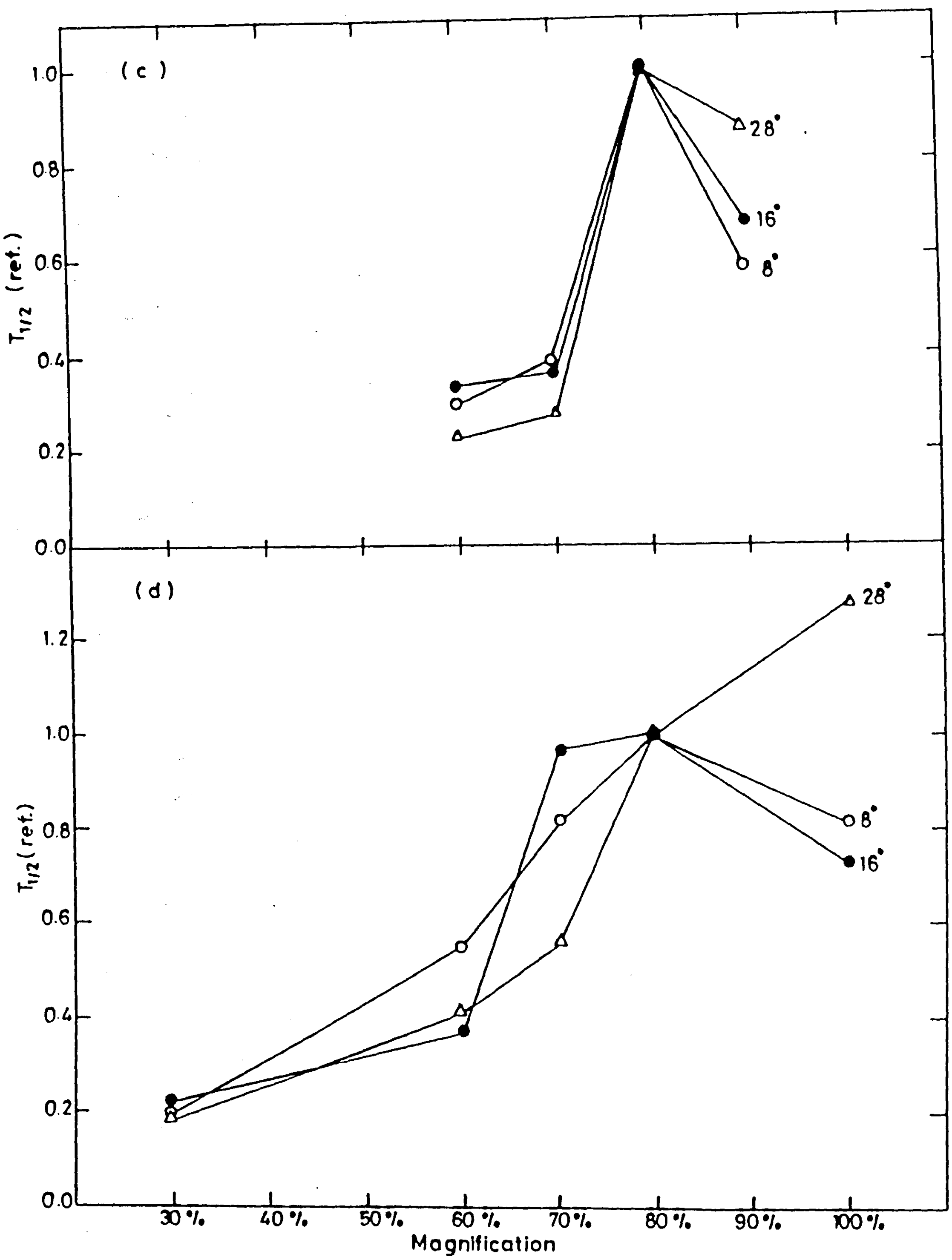

FIG. 5-10 c,d. Orientation discrimination data for square elements of mixed orientation and magnification taken from Figure 5-10 a,b. $T_{1/2}$ values for 40 reference elements normalized for the 80% magnification are plotted against magnification of the variable reference element. (c) represents data of 5-10a, (d) represents data of 5-10b.

magnification discrimination were investigated in a series of experiments corresponding to those described in the previous section. In the preliminary experiments, measurements were made with two classes of reference element, both of the same orientation but of different magnification. The targets were distinguished from the reference elements in orientation and were matched in size to one of the two reference elements, (see Fig 2-10c). In subsequent experiments, the reference fields consisted of two classes of elements which differed from each other in both magnification and orientation, and the target orientation matched that of one of the reference elements. Both triangular and square elements were used in the experiments.

5.4.2.1. <u>Results:</u>

Data from experiments in which the two classes of reference element have the same orientation are given in Fig 5-11 (for triangles) and Fig 5-12 (for squares). The results indicate that for the smallest targets, $T_{\frac{1}{2}}$ values obtained with the mixed reference field are considerably larger than those obtained with reference fields consisting of only one of the two classes present in the mixed reference field. As the size of the target increases, however, these differences are reduced, so that with the largest target, there is effectively no difference between the values obtained with the mixed and those obtained with the simple reference field. These results indicate that even when the reference elements differ in orientation from the target, mixing different sized reference elements can cause an increase in $T_{\frac{1}{2}}$ values for magnification discrimination. Independence between the two parameters is not, therefore, observed, particularly for small target sizes.

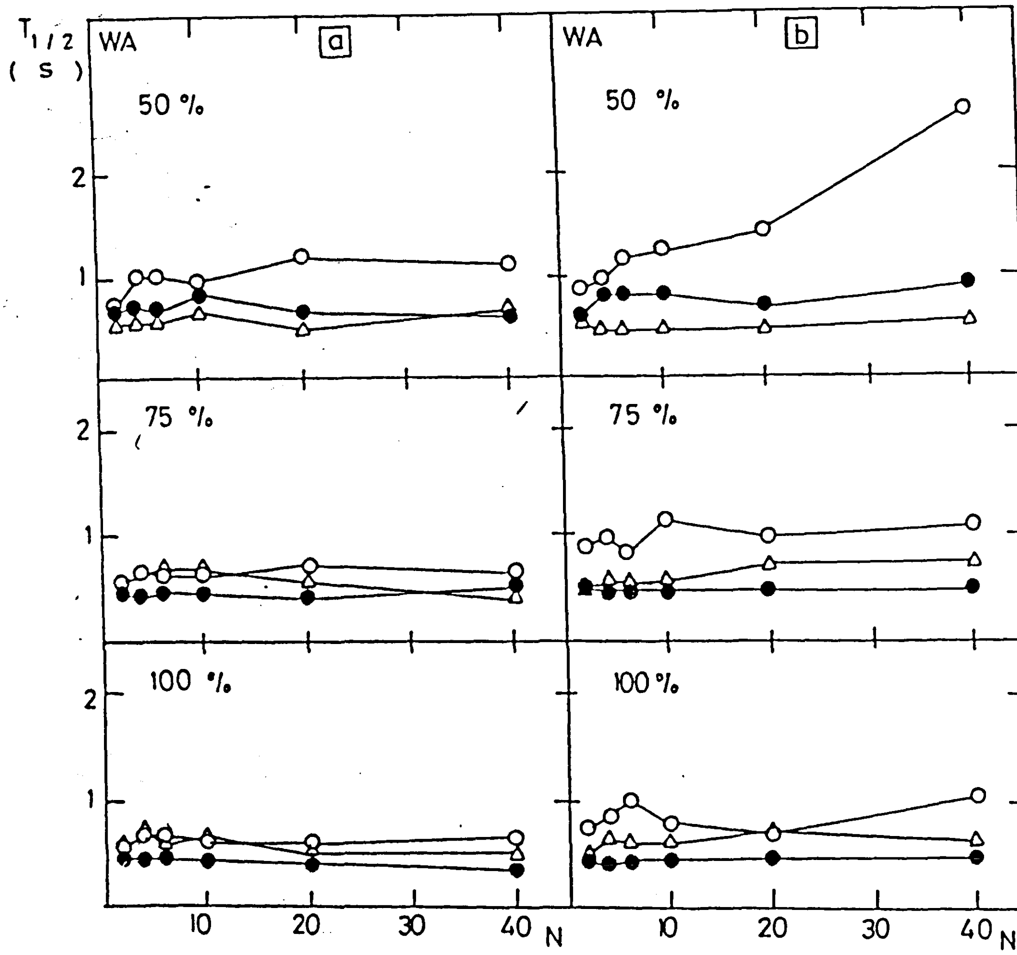

FIG. 5_11 . Magnification discrimination for triangular elements of mixed orientation and magnification. The targets were of size and orientation specified on the plots. (a) Target orientation 90° (▶), and reference field oriented upright (▲) of relative size 100% and 50% (○); 100% (△) and 50% (●). (b) Target orientation 0° (▲) and reference elements were oriented at 90° (▶) of relative size 100% and 50% (○); 100% (△) and 50% (●).

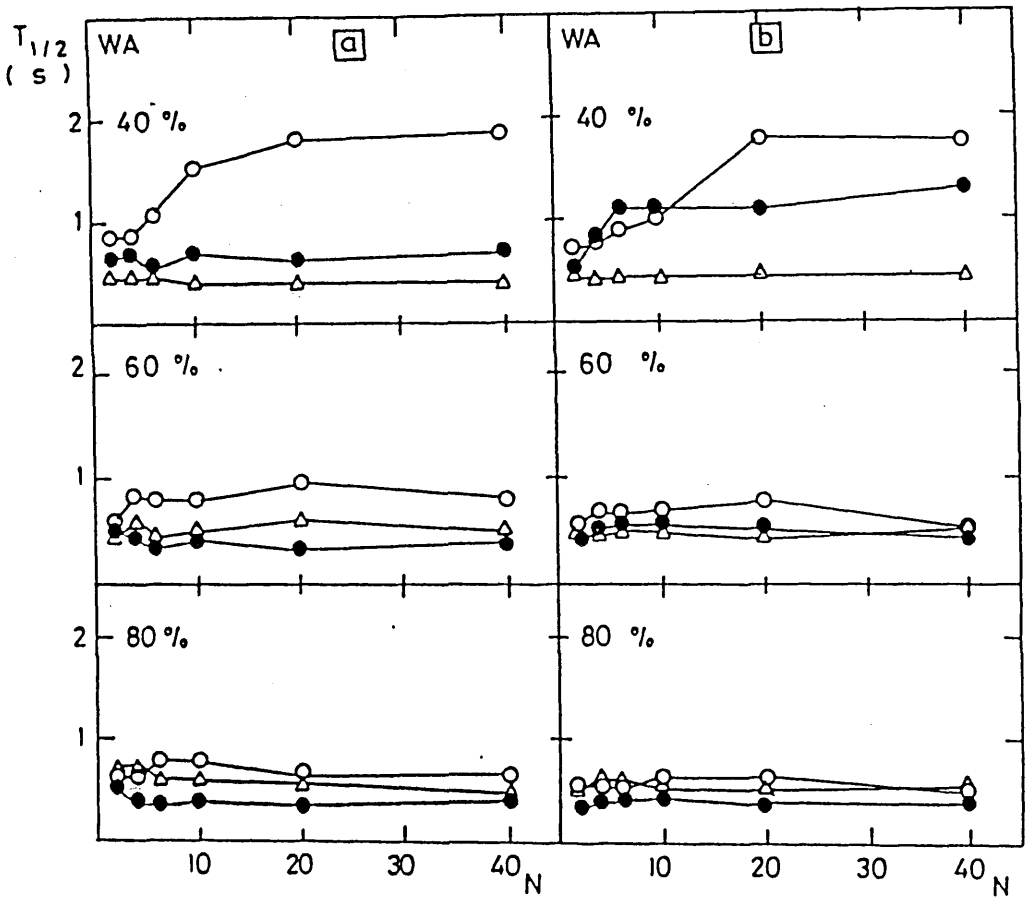

FIG. 5 _ 12. Magnification discrimination for square elements of mixed orientation and magnification. The target size is marked on the plots. (a) The target is oriented upright (■). The reference elements were oriented 45° (◆) and of sizes: 80% and 40% (O); 80% (Δ); and 40% (●). (b) The target is oriented 45° (◆). The reference elements were oriented upright (■) and of sizes: 80% and 40% (O); 80% (Δ); and 40% (●).

Data obtained in experiments with the two classes of reference elements distinguished both by orientation and magnification are illustrated in Fig 5-13 (for triangles) and Fig 5-14 (for squares). The results for the mixed reference elements demonstrate that the effect of the mixed reference elements is, in nearly all cases, similar for both combinations of the reference elements, that is, the effect of the mixed reference field on magnification discrimination is independent of the orientation of the elements. In only one case (100% target, rotation of the large element) does rotation of one class of element reduce the effect of the reference field.

In order to study further the effect of varying the reference orientation, measurements were made for a series of mixed fields in which one of the two square shaped elements was changed in orientation relative to the other, which always matched the target in orientation. Results presented in Fig 5-15 show that when the smaller class of reference element is rotated, values of $T_{\frac{1}{2}}$ vary relatively little. This is shown more clearly by plotting $T_{\frac{1}{2}}$ values against the reference element orientation for the case where there are 40 reference elements (Fig 5-16). And the values of $T_{\frac{1}{2}}$ vary rather little as the orientation difference between the target and reference element increases. Similar results were obtained when the larger reference element is rotated. Fig 5-17 shows $T_{\frac{1}{2}}$ values against the reference element orientation for the case where there are 40 reference elements. It is apparent that for each combination of target and reference element, there is little variation of $T_{\frac{1}{2}}$ with O, that is, the discrimination is not dependent on the orientation of the reference elements from which the target is discriminated.

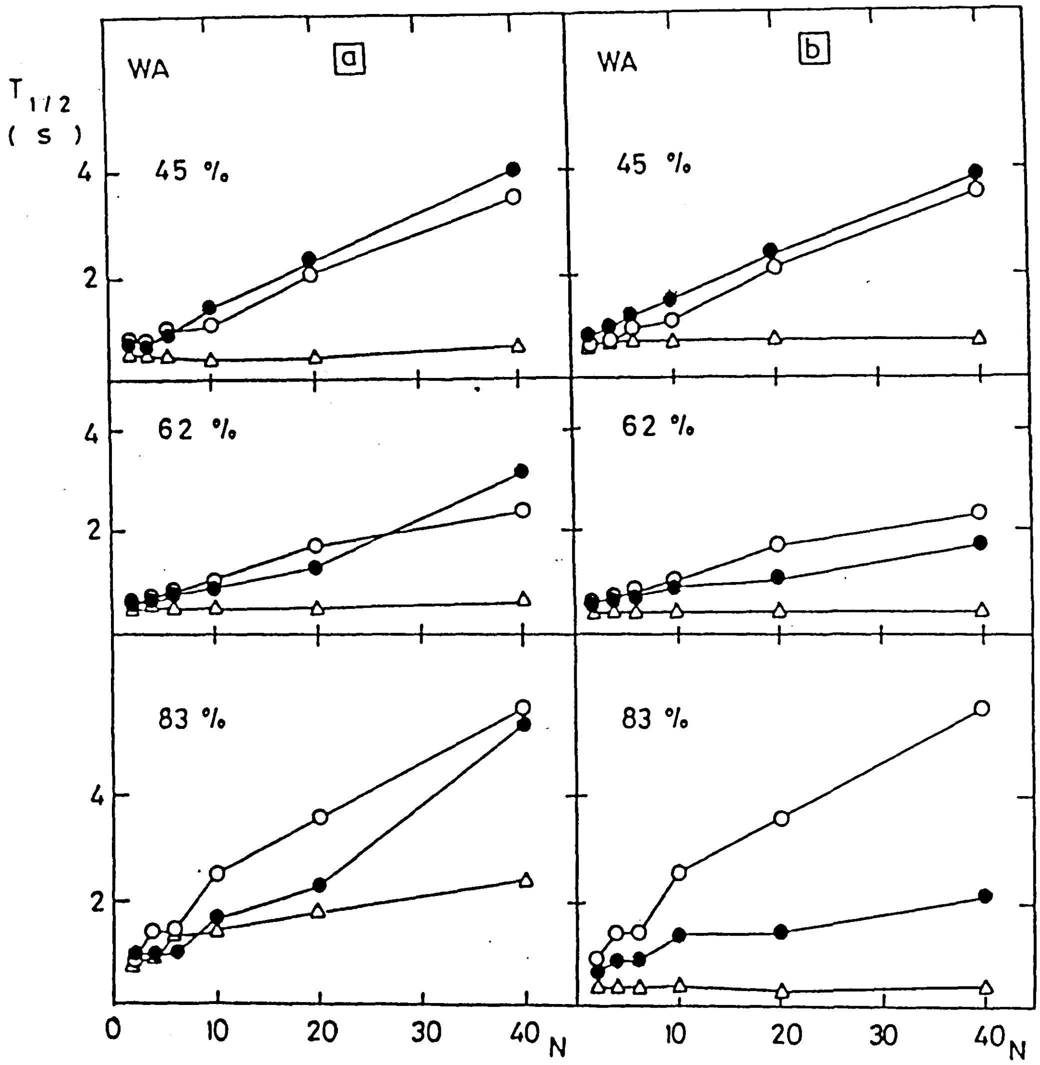

FIG. 5 _ 13 . Magnification discrimination for trianglular elements of mixed orientation and magnification. The target is oriented upright (▲) and its relative size is specified on each plot. (a) The reference elements were ▲ 100% and ▲ 30% (O); ▲ 100% and ◀ 30% (●); and ▲ 100% (Δ). (b) The reference elements were ▲ 100% and ▲ 30% (O); ◀ 100% and ▲ 30% (●); ▲ 30% (Δ).

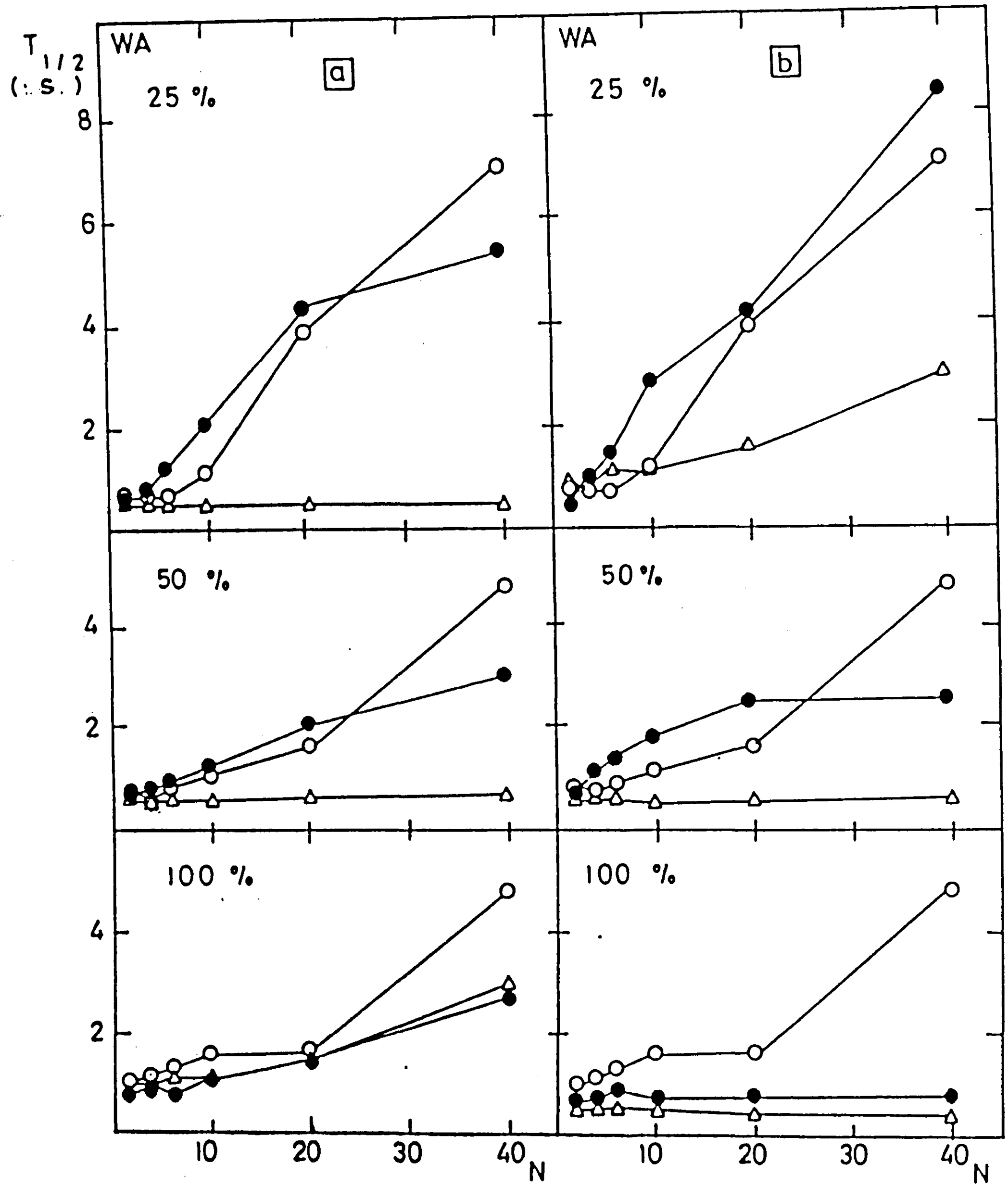

FIG. 5-14a,b: Magnification discrimination for square elements of mixed orientation and magnification. The target size is given with each plot, and is oriented upright (■). (a) The reference fields were: ■ 80% and ■ 31% (O); ■ 80% and ◆ 30% (●); and ■ 80% (Δ). (b) The reference fields were: ■ 80% and ■ 33% (O); ◆ 80% and ■ 33% (●); and ■ 31% (Δ).

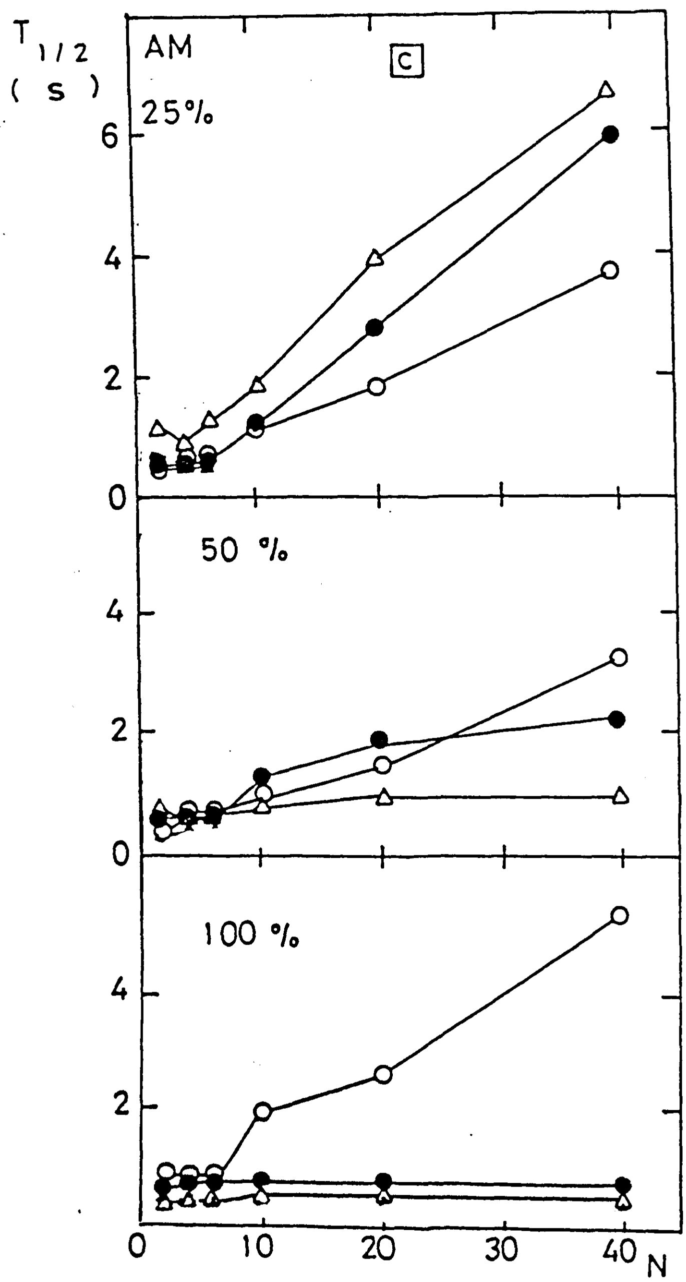

FIG. 5_14_c· As Fig. 5-14b, but for subject AM.

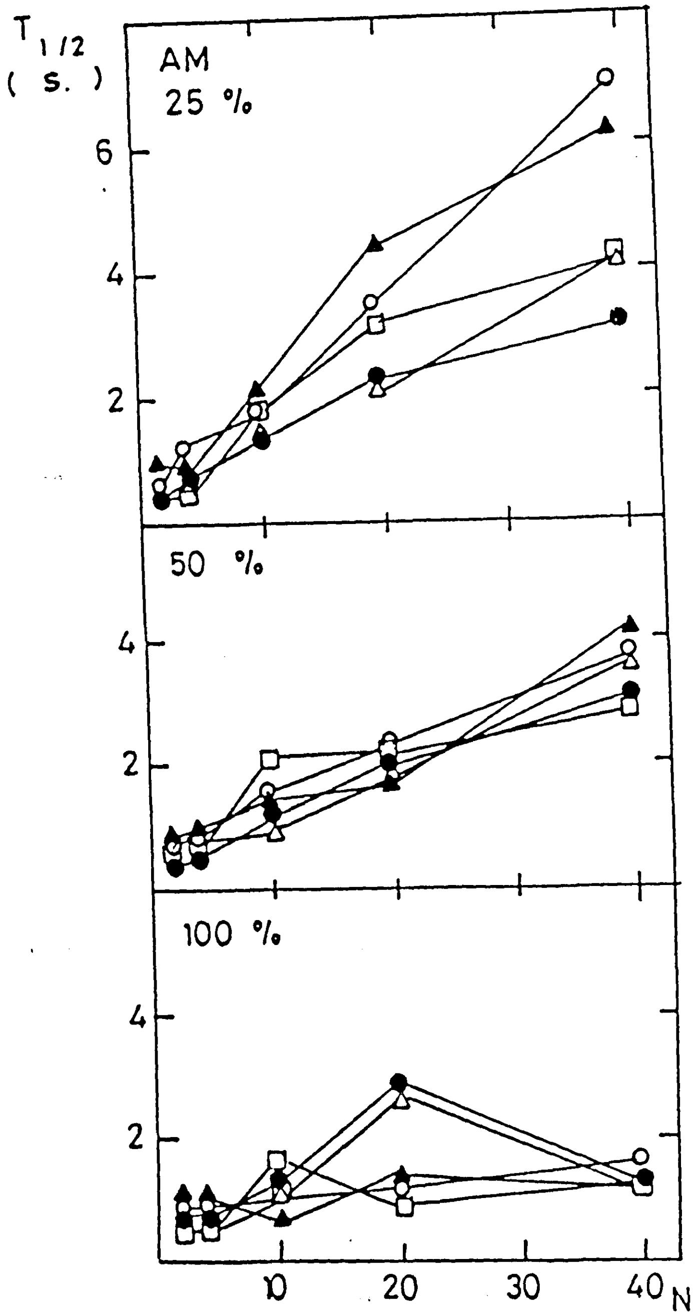

FIG. 5 _ 15: Magnification discrimination for square elements of mixed magnification and discrimination. The targets were oriented upright (■) and of size specified on the plots. The reference elements were: ■ 80% and a 33% element of orientation 0° (▲), 10° (○), 20° (△), 30° (□) and 40° (●).

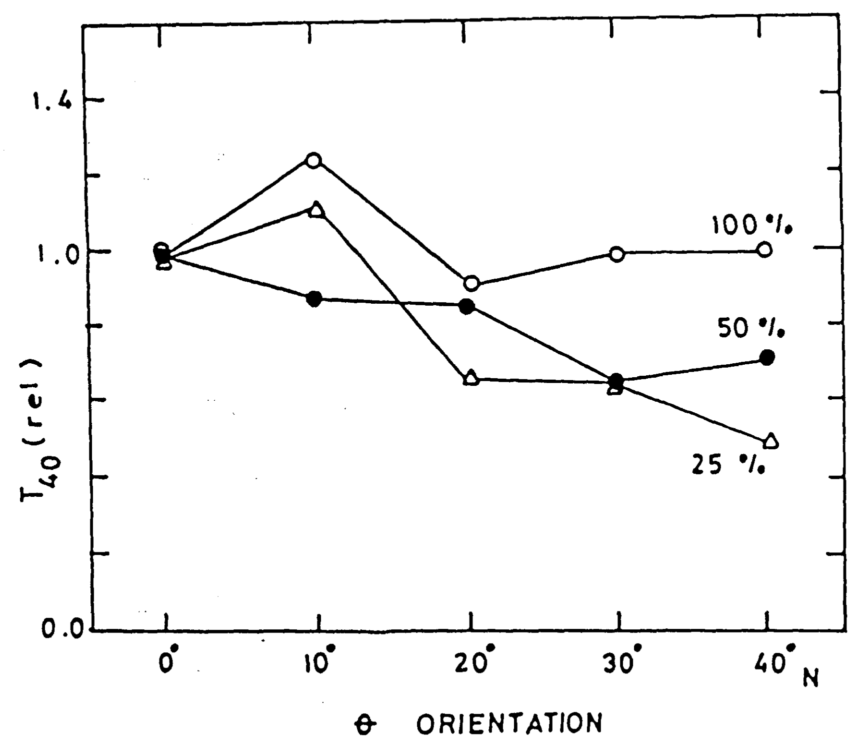

FIG. 5-16. Magnification discrimination data for square elements of mixed magnification and orientation taken from Figure 5-15. $T_{\frac{1}{2}}$ values for 40 reference elements normalized for $\theta = 0$ are plotted against the angle θ, of the 33% reference element.

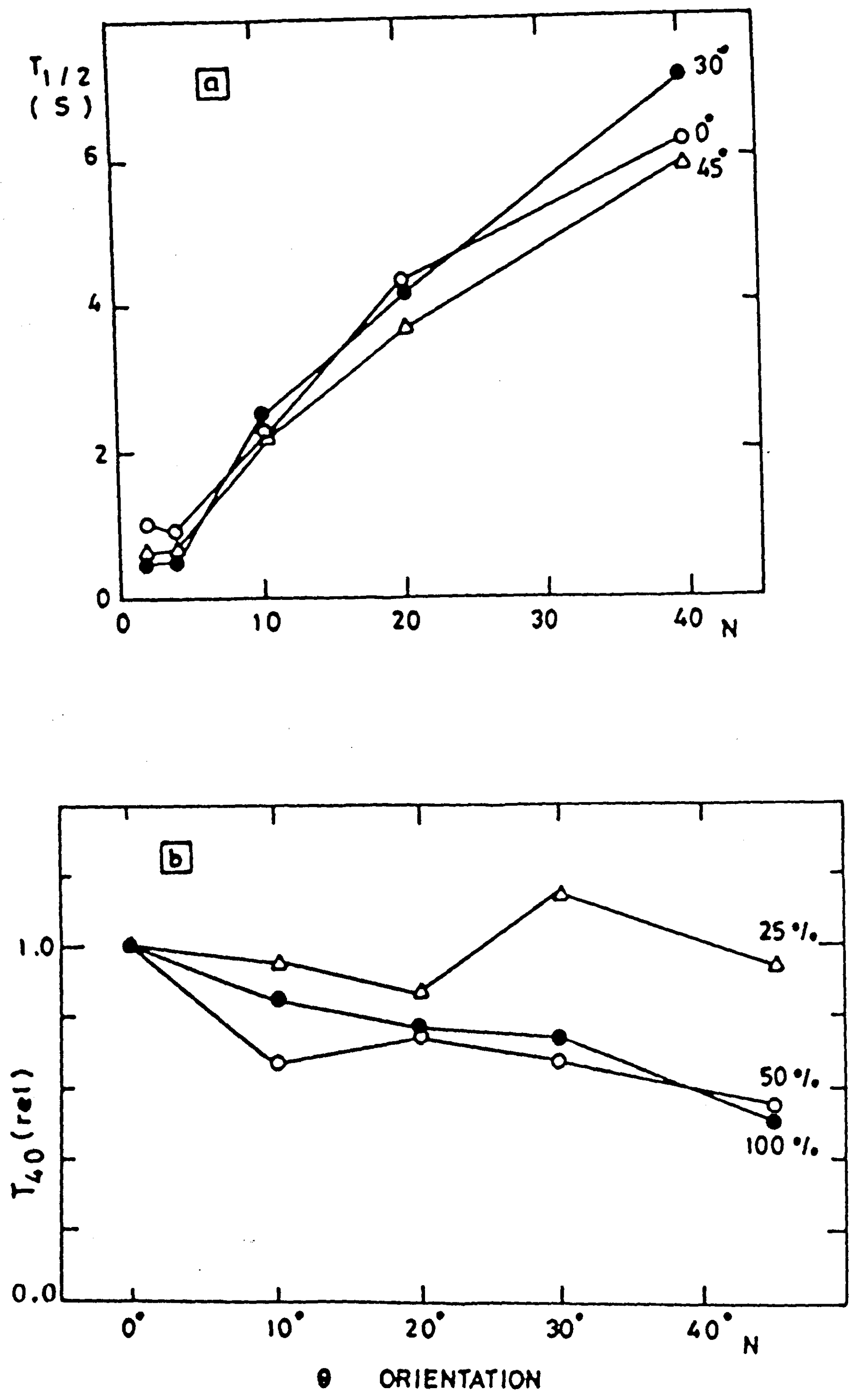

FIG. 5-17: As Fig. 5-15, but with the rotation of the large (80%) reference element.

(a) Sample data obtained.

(b) As Fig. 5-16. Data for $T_{1/2}$ values for 40 reference elements plotted against the angle θ of the 80% reference element.

5.5. Conclusion:

Measurements have been made with two classes of reference elements, which differ both in magnification and in orientation from each other. When the target is distinguished from both classes of reference elements by its relative orientation a difference in magnification between the target and one class of reference element makes the discrimination easier, that is discrimination of orientation is tuned to magnification. In contrast, when the target is distinguished from both classes of reference elements by its relative magnification, a difference in orientation between the target and one class of reference element has little influence on the discrimination task. It appears, therefore, that discrimination of magnification is mediated by mechanisms which are not sensitive to orientation.

CHAPTER SIX

6. Relative Luminance Measurements:

6.1. Introduction:

In this Chapter I describe two sets of experiments. The objective for the first set was to determine the limits for distinguishing the target on the basis of luminance difference. The target was, therefore, presented in a reference field matched in orientation and magnification to the reference elements. The target had either a higher or a lower value of luminance relative to that of the reference field, which consisted of a single class of identical elements. The elements were, in all cases, green with a black background and measurements were made for a number of different luminance levels of the reference field. The luminance values of the reference elements and the corresponding contrast levels of the target, defined as $\frac{L_T - L_R}{L_T + L_R}$, where L_T is the target luminance and L_R the reference luminance, are given in Table 6-1. The target elements were in the form of equilateral triangles of base length 0.45 deg. Data are given for a single subject W.A.

In the second set of experiments the reference field consisted of two classes of element which differed in orientation and relative luminance, with the target matched in luminance to one class of reference element, but different in orientation from both classes. The experiments were executed twice; first with green and then with red elements, the background in both cases being black. Measurements were made for a number of relative luminances for one class of reference element (see Table 2-2, in Chapter Two, for the various combinations of colour and luminance).

Table 6-1. Relative Luminance of Green Reference and Target Contrast used in Luminance Discrimination Measurements.

Reference		Target Contrast		
Gun Value	Relative Luminance			
220	1.33	-0.091	-0.182	-0.273
160	0.64	0.125	0.250	0.375
160	0.64	-0.125	-0.250	-0.375
140	0.41	0.143	-0.143	-0.286
120	0.24	0.333	0.167	-0.167
100	0.10	0.600	0.400	0.200
100	0.10	-0.150	-0.300	-0.450
85	0.041	0.177	-0.177	-0.353
80	0.022	-0.375	-0.250	-0.125

6.2. Results:

6.2.A. Luminance Discrimination:

As in all other experiments described in this thesis, $T_{\frac{1}{2}}$ was measured as a function of N, the number of reference elements in the background field, and a typical set of data are illustrated in Fig 6-1. In order to compress the large number of data into few graphs, I have plotted $T_{\frac{1}{2}}$ against the target relative

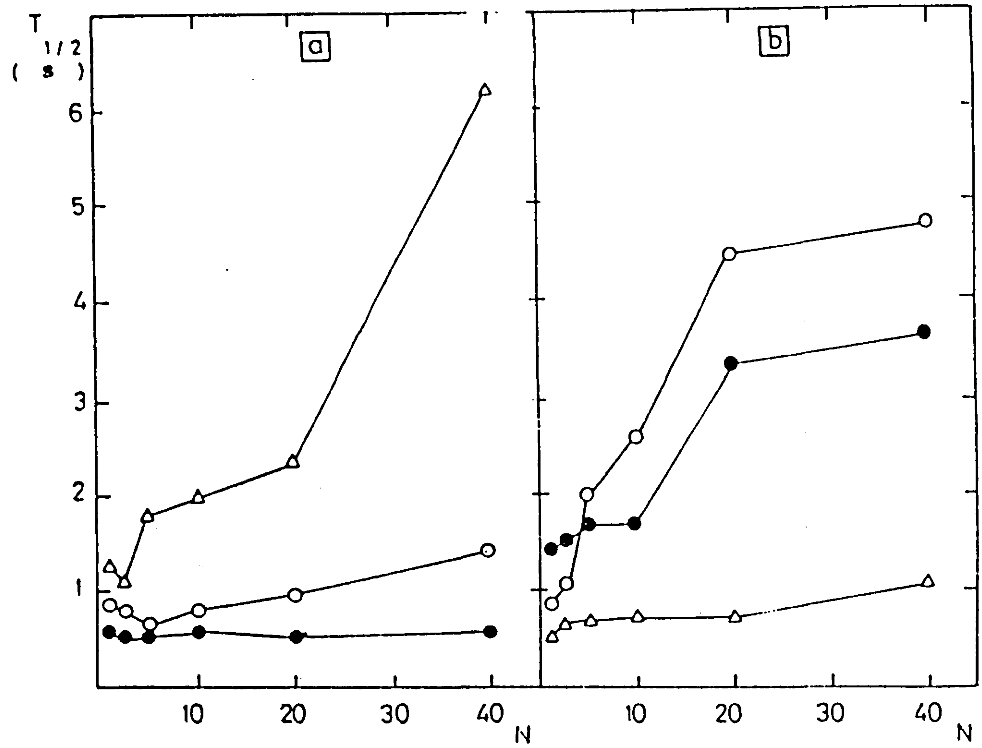

FIG. 6-1. Luminance discrimination measurements with $T_{1/2}$, the time for 50% probability of target detection, plotted against N, the number of reference elements. All elements were matched, upright triangles. (a) The reference elements were of relative luminance 0.24 and the target of relative luminance 0.64 (●), 0.41 (○) and 0.10 (△). (b) The reference elements were of relative luminance 0.41 and the target of relative luminance 0.64 (●), 0.24 (○) and 0.10 (△).

luminance, for a single value of N, but for all the different luminance levels of the reference field. The data for N equal to 1,5,10 and 40 are plotted in Fig 6-2, 6-3, 6-4 and 6-5 respectively, and data for two different ranges of reference luminance are distinguished by different symbols. Thus values for reference elements of relative luminance 0.24 to 1.33 are denoted by full circles and those for reference of relative luminance 0.022 to 0.10 by triangles. The results show the expected trend, namely that as N increases the values of $T_{\frac{1}{2}}$ increase, and that as relative luminance tends to zero, the values of $T_{\frac{1}{2}}$ increase. It should be noted that as the relative luminance of the background increases, values of $T_{\frac{1}{2}}$ increase from their minimum value at contrasts further from the matching value 1.0. For example with N equal to 40, $T_{\frac{1}{2}}$ reaches its minimum level at a contrast of about ±0.3 for the brighter range of reference luminances, but for the successive lower luminance this occurs at contrasts of about ±0.25. Thus in assessing performance in detection of these targets, it is insufficient to define target contrast but the absolute luminance of the element should also be defined. These results show that for maximum performance, contrast level differences of 10% to 30% are required between the target and the reference element. In similar experiments, Javadnia and Ruddock (1988b) showed that for elements presented against a background, luminance contrasts of 5% to 10% were required in order to achieve maximum discrimination of spatial parameters in a target. These figures for peak discrimination performance compare with a level of 1% for simple detection of a target superimposed on a background field.

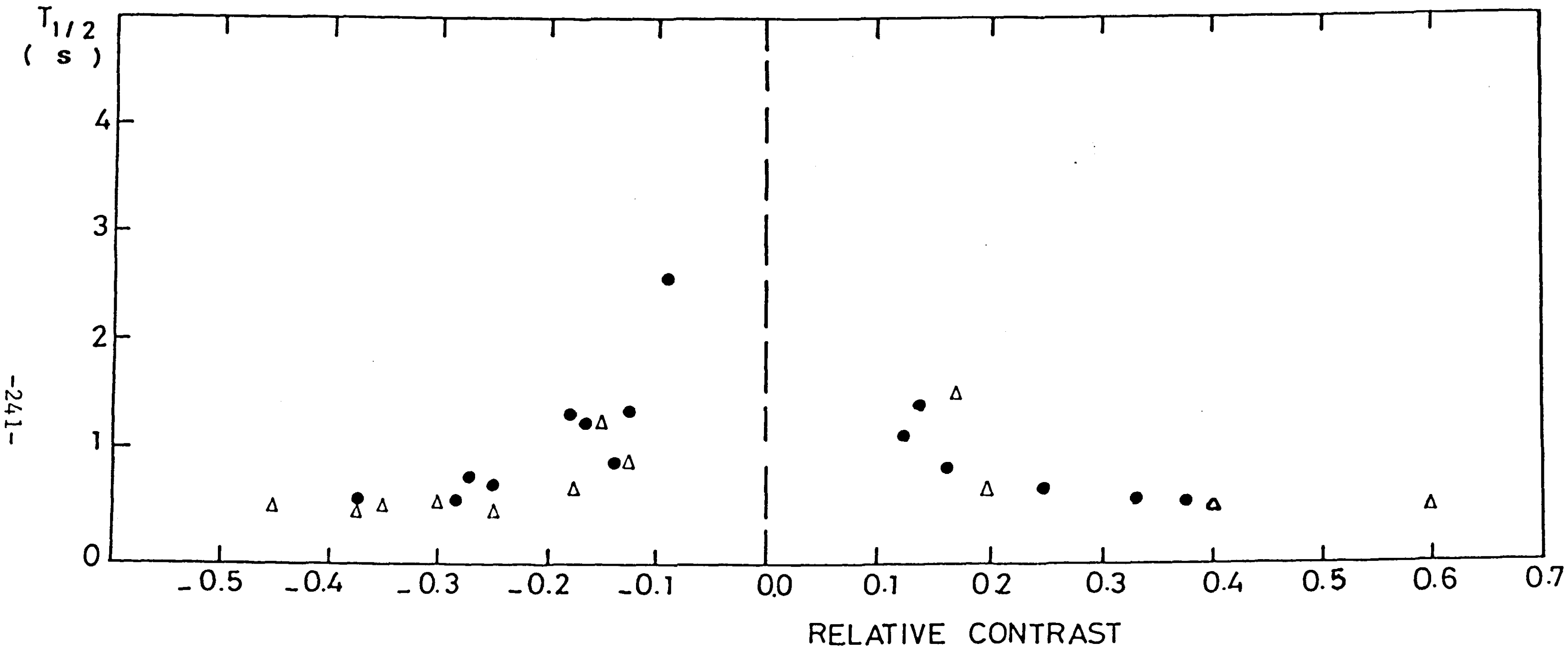

FIG. 6-2. Luminance data taken from plots such as Figure 6-1. $T_{1/2}$ values for N=1 are plotted against the relative luminances of the target, and the different symbols correspond to different relative luminance ranges of the reference elements. Thus (Δ) corresponds to the range 0.022 to 0.10 and (●) to the range 0.236 to 1.33.

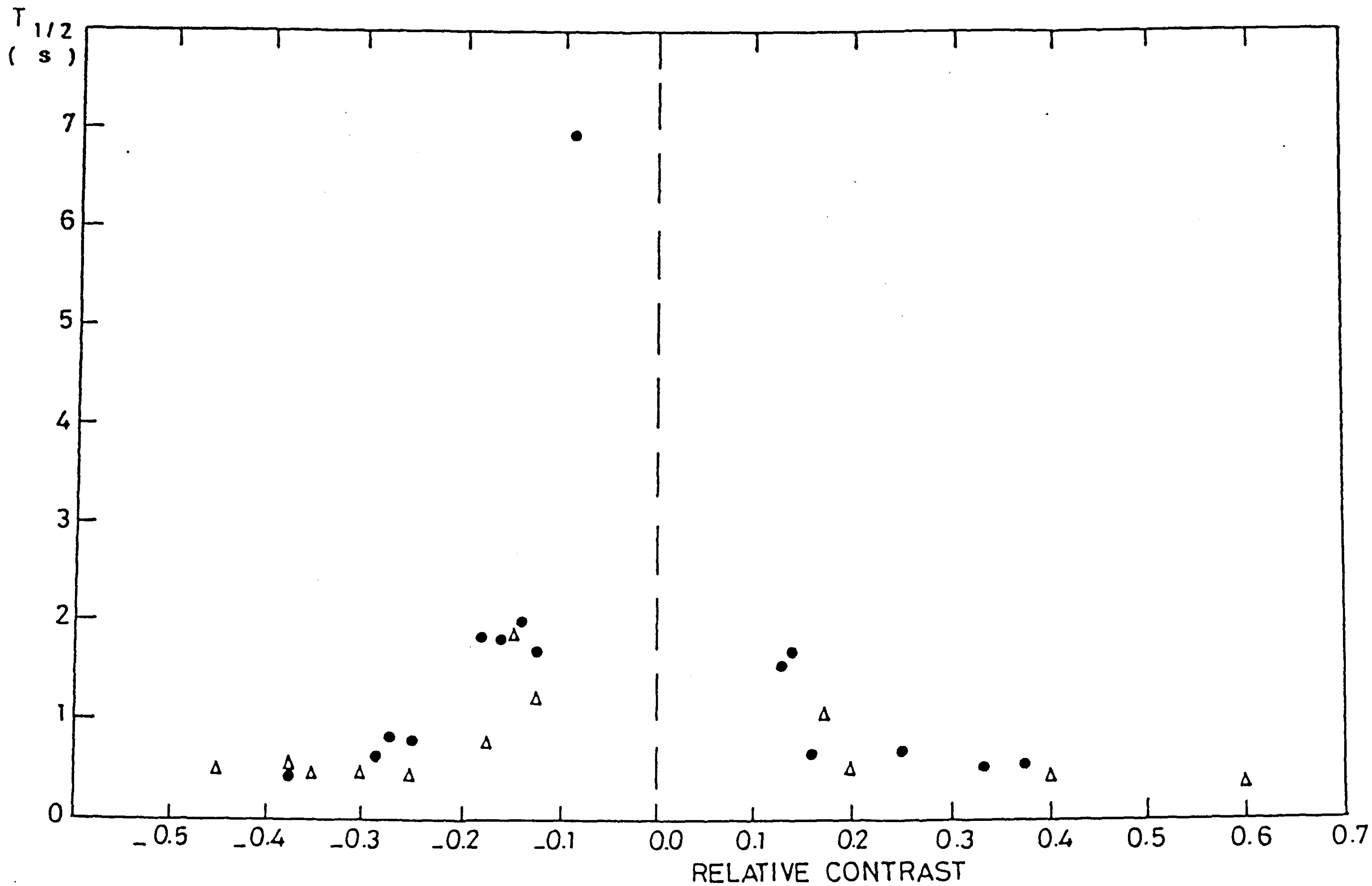

FIG. 6-3. As for Figure 6-2, but with N=5.

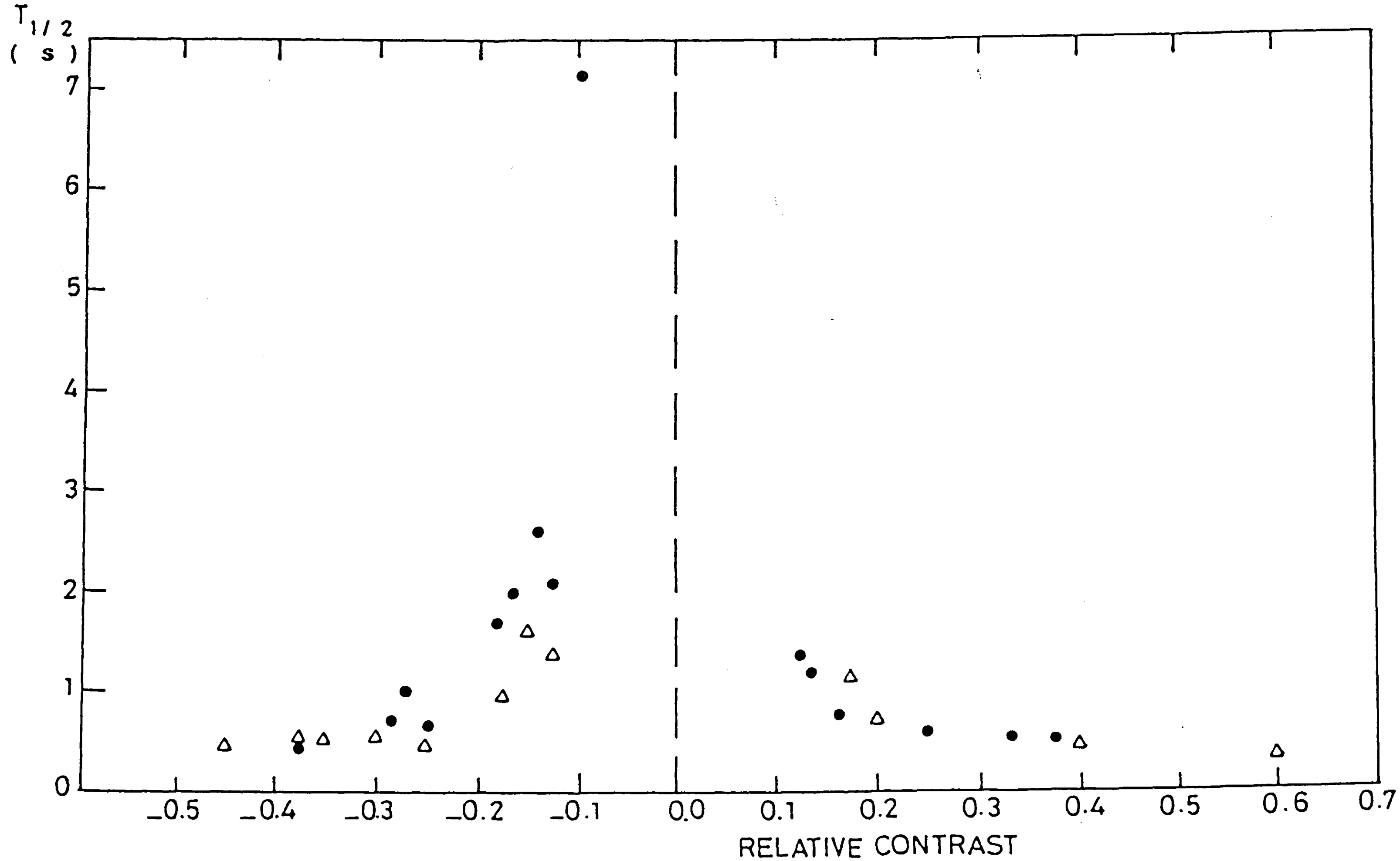

FIG. 6-4. As for Figure 6-2, but with N=10.

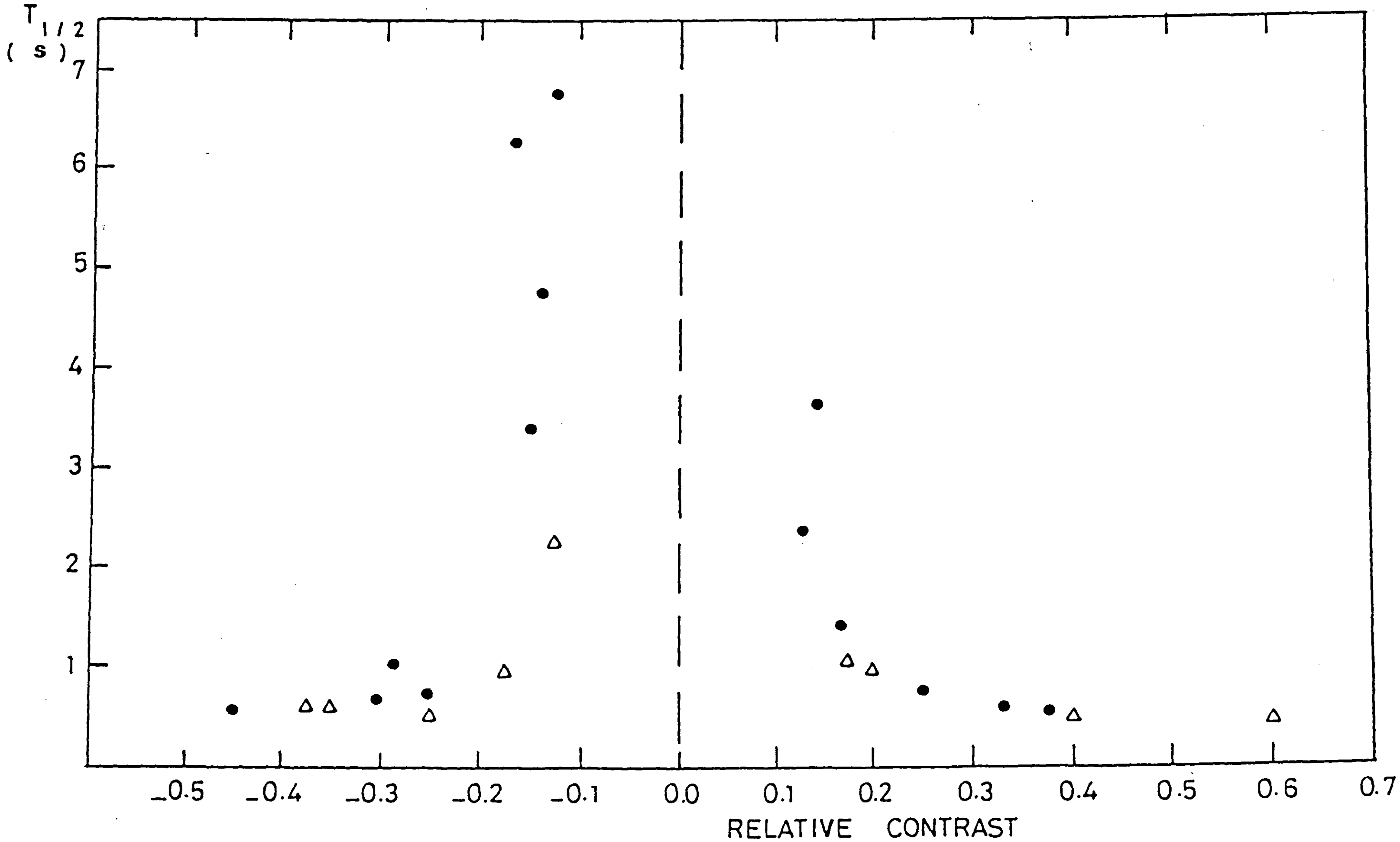

FIG. 6-5. As for Figure 6-2, but with N=40.

6.2.B. Orientation Discrimination with Variable Luminance in One of Two Classes of Reference Elements:

The method used in the previous experiments (e.g. Chapter 3) in which two classes of reference element differed in their parametric properties was applied. In these experiments, two classes of reference elements which differed in relative luminance and orientation were used. $T_{\frac{1}{2}}$ was measured as a function of N, the number of reference elements, which consisted of equal numbers of the two classes of reference element. A sample of the results is shown for three target orientations in Fig 6-6. Measurements were made for both red and green elements in order to compress the large number of data obtained into few graphs. I have plotted $T_{\frac{1}{2}}$ against the relative luminance of the variable class of reference element. Data are presented for N=2, 10 and 40 only, for each target orientation separately. Data are presented in Figs 6-7, 6-8 and 6-9 for 8 deg., 16 deg. and 23 deg. orientation of the target respectively. In each figure, plot (a) is for green elements and (b) is for red elements.

Results show that target discrimination is based mainly on orientation differences and that the differences in luminance between the two classes of reference elements did not cause any systematic change in values of $T_{\frac{1}{2}}$. This implies that the orientation discrimination mechanism is relatively insensitive to differences in luminance.

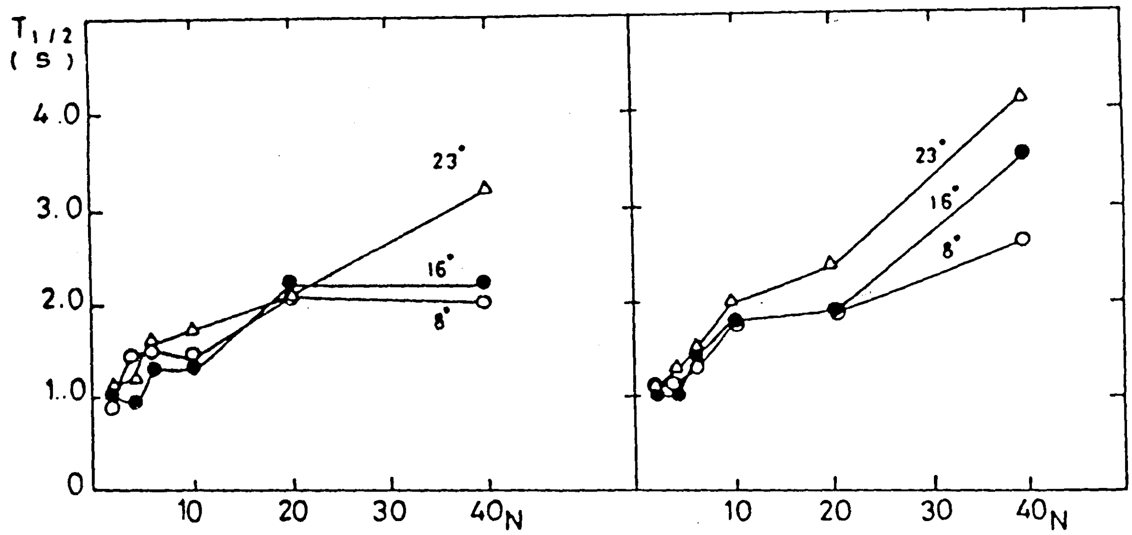

FIG. 6-6. Luminance and orientation discrimination measurements with reference field of mixed orientation and luminance. Targets were of relative luminance 1.0 and orientation as noted on the data. (a) For two classes of reference elements, one an upright triangle with relative luminance 1.0 and the other a triangle rotated through 30°, of relative luminance 1.07. (b) For two classes of reference elements, one an upright triangle with relative luminance 1.0 and the other a triangle rotated through 30° of relative luminance 0.90.

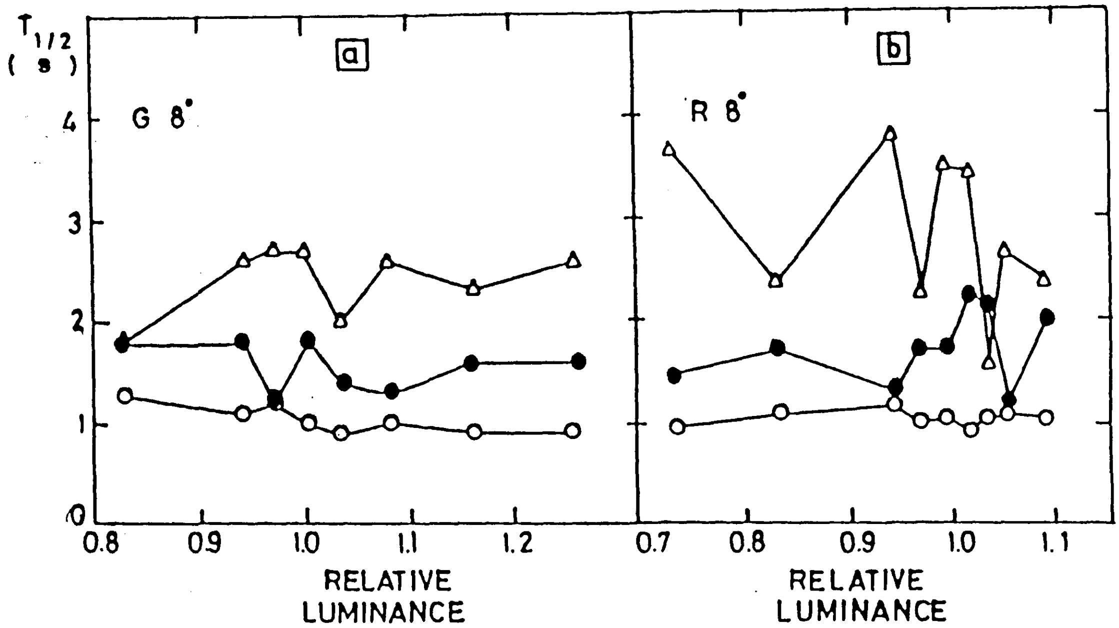

FIG. 6 -7. Orientation discrimination with luminance differences between the triangular elements. The reference field consisted of a mixture of two reference classes of element, upright triangles (▲) with relative luminance 1.0, and triangles at 30° (◀) set at a series of relative luminances. $T_{\frac{1}{2}}$ values are plotted against the relative luminance of the latter class of reference element, and data are given for three values of N, the number of reference elements. 2(○), 10(●) and 40(△). The target orientation was 8°, and the target was of relative luminance 1.0.
(a) Green elements, (b) Red elements.

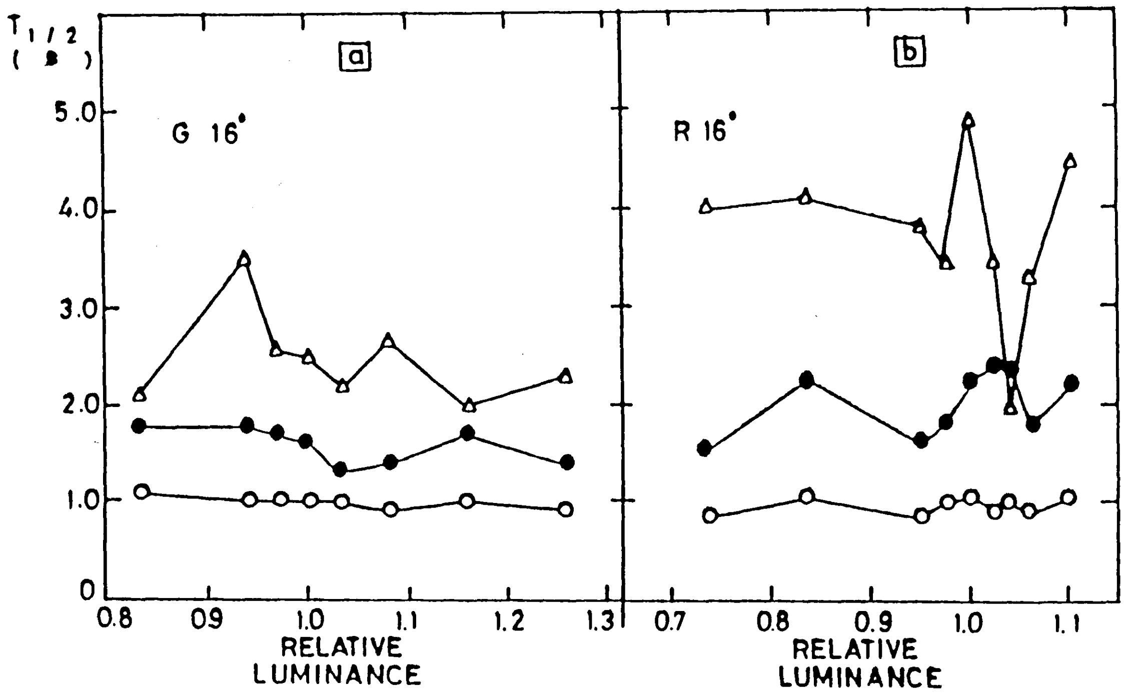

FIG. 6 _8 . As Figure 6-7, but for target orientation equal to 16°.

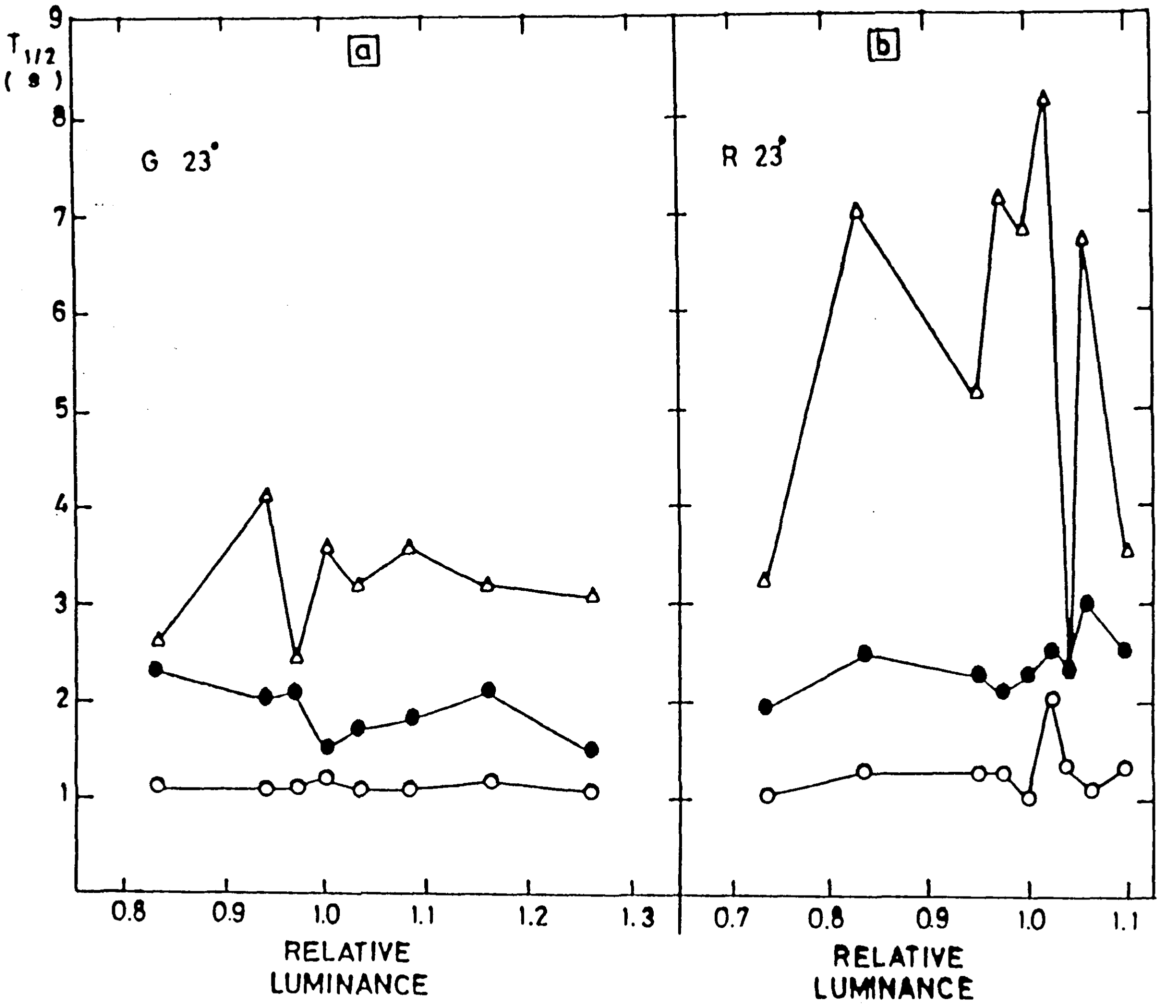

FIG. 6 - 9 . As Figure 6-7, but for a target orientation of 23°.

CHAPTER SEVEN

Page No.

Chapter Seven

Recognition of Complex Patterns

7.1. Introduction:

In previous experiments, measurements were made with simple reference elements. In this Chapter, I examine the effect of using more complex elements, and in particular, of introducing circles with triangles for the measurement of orientation or magnification discrimination. In a previous study (Ike et al., 1987) such elements were introduced in order to increase the response time $T_{\frac{1}{2}}$. I have studied this phenomenon by using a greater variety of elements.

7.2. Experimental Procedure:

The experiments were performed with reference fields consisting of 40 identical complex elements (Fig 2-11) with targets which differed from them in either orientation or magnification from the reference elements. The half time, $T_{\frac{1}{2}}$, was measured for each target.

7.3. Subjects:

The subjects were two post graduate students at Imperial College, I.M. male and W.A. female, both with 6/6 visual acuity.

7.4. Results:

In this section the results all refer to reference fields consisting of 40 elements only, and they are presented graphically, with $T_{\frac{1}{2}}$ values plotted against either the magnification or the orientation of the targets.

7.4.1. Orientation Measurements:

The first set of results (Fig 7-1) were for four reference fields consisting of shapes made of triangles pointing upwards combined with circles and targets which differed in the orientation of the triangle component. The first reference field was made up of a small triangle in a circle (Fig 7-1a), then as the triangle size increased the second shape gave triangles the corners of which just touched the circumference of the circle (Fig 7-1b), the third step was a triangle which intersected the circumference of the circle (Fig 7-1c), the last step was a small circle within the triangle, with its borders just touching the sides of the triangle (Fig 7-1d). These results show that $T_{\frac{1}{2}}$ values are highest when the triangle is completely embedded in the circle for all orientations and as the triangle moves outward and its corners emerge from the circle, $T_{\frac{1}{2}}$ values decrease and became similar to the values obtained without the circles. These results indicate that the addition of the circular component interferes with orientation discrimination when it forms the outer limit of the elements, but not when it is enclosed by them. It is particularly interesting to observe that when the circle intersects the triangle, forming what in some ways is a more complex figure, it has less effect on discrimination than when the circle surrounds the triangle.

Similar experiments were performed, but with the corners removed from the triangular components of the elements. The targets were of similar structure, but the triangular elements were rotated relative to the

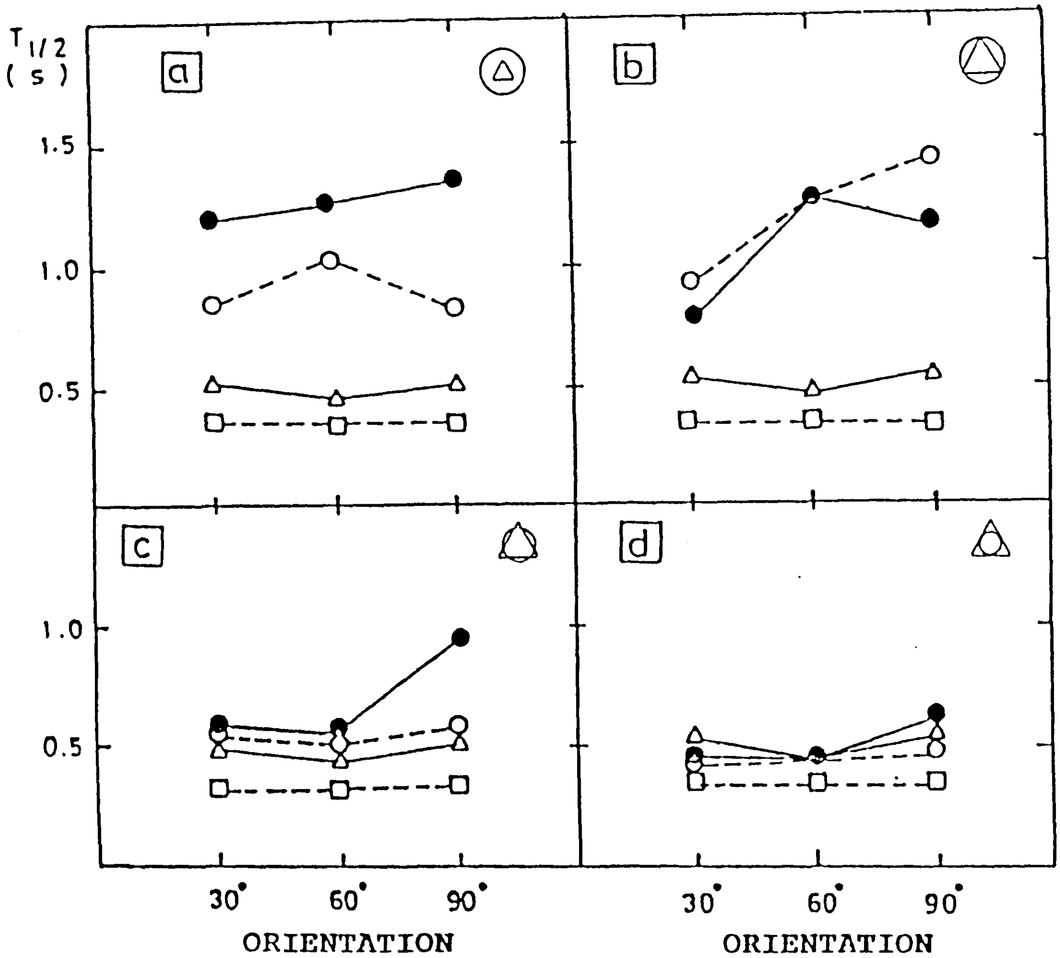

FIG. 7-1. Orientation discrimination with complex elements. $T_{1/2}$ is plotted against θ, the orientation angle of the target. The reference elements were as indicated at the top right of each plot, and values are also given for similar elements without the circles. The target element matched the reference elements, except for the orientation of the triangular component. There were 40 reference elements in all cases.

Data with circles:
(○) Data for subject IM.
(●) Data for subject WA.

Data without circles
(□) Data for subject IM.
(△) Data for subject WA.

upright orientation of the reference elements. $T_{\frac{1}{2}}$ values are plotted against the relative orientation of the target (Fig 7-2), and it is apparent that in this case the surrounding circles have little influence on the response. Thus, the processing of continuous triangles in orientation discrimination appears to be different from that of the cornerless triangles. Previous studies by Ike et al., (1987) and Ike and Ruddock (1987) both led to a similar conclusion regarding differences in orientation discrimination between elements such as  and  .

Other experiments were performed in which orientation discriminations were performed for targets which differed from the reference elements both in structure and in orientation. The elements were constructed from two components, a surrounding circle and a triangle shaped component, the reference elements being continuous triangles, oriented upright, and just enclosed in a surrounding circle (i.e. ). The various targets are illustrated in Fig 7-3 and these were presented at four different orientations. For comparison, measurements were also made without a surrounding circle. The experimental data are plotted in Fig 7-3 and show that $T_{\frac{1}{2}}$ values measured for elements with surrounding circles are greater than the corresponding values without the circles. The effect is particularly marked for targets with upright orientation, where no orientation clues are available. A similar set of measurements, in which the reference elements were of the form (), and the targets were of the form (), presented at various orientations as noted in Fig 7-4. $T_{\frac{1}{2}}$ is again significantly lower when the elements have no surrounding circles, and again, the effect is most marked when the targets have

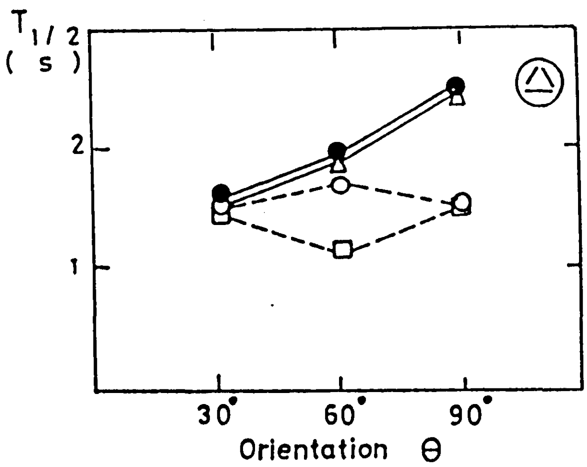

FIG. 7_2 . Orientation discrimination for the complex pattern shown in the upper right corner. The target was identical to the reference elements, except rotated through angle θ.

(●) Data for subject WA with circles.
(○) Data for subject IM with circles.
(△) Data for subject WA without circles.
(□) Data for subject IM without circles.

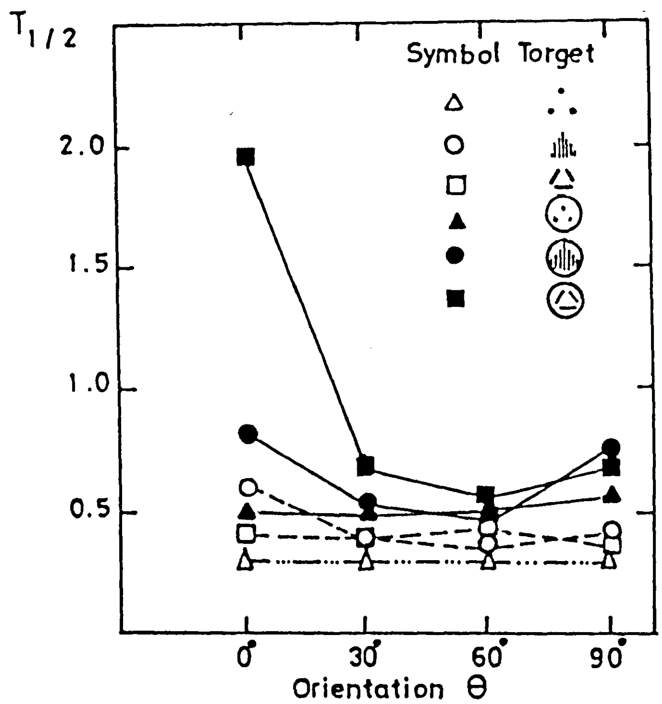

FIG. 7-3. Orientation discrimination with complex patterns. The reference elements were either ◬ or △, and the targets are illustrated in the figure.

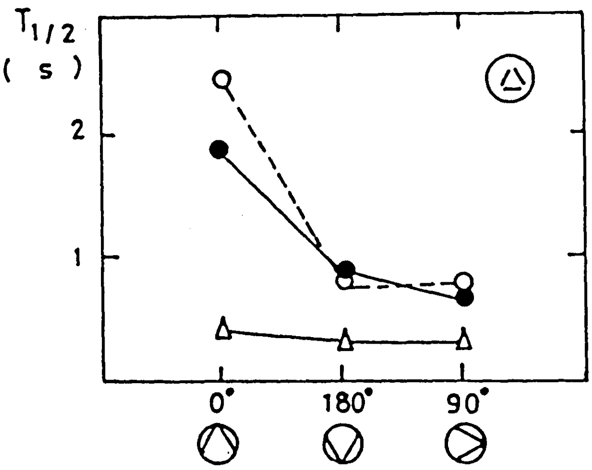

FIG. 7_4 . Orientation discrimination with complex patterns. The reference elements are illustrated in the upper right corner and the targets below the axis. Results for 40 reference elements.

(●) Data for subject WA with circles.
(O) Data for subject IM with circles.
(Δ) Data for subject WA without circles.

the same orientation as the reference elements (Fig 7-4). Thus both experiments establish that the addition of circular components makes orientation discrimination more difficult, even when there are difference in shape as well as in orientation.

7.4.2. Magnification Measurements:

The experiments were performed with reference elements consisting of an equilateral triangle within a circle, its corners touching the circumference of the circle, and targets for which the length dimensions of this triangle were varied in magnification equal to 3/4, 1/2 and 1/4 the side length of the reference triangles. Measurements were also made with reference elements in which the triangle had linear size of 1/4, and targets of relative size 1/2, 3/4 and 1, the last of which just fitted into the surrounding circle. In all experiments, the circles were of the same size. Data are presented in Fig 7-5 in which $T_{\frac{1}{2}}$ values are plotted against linear magnifications. The values for measurements made with the circles are greater than those made without them, thus, magnification discrimination is also influenced by the addition of a surrounding circle.

7.4.3. Luminance Discrimination:

Measurements were also carried out with the same reference field (triangle within a circle) but the targets were discriminated by the difference in the luminance of the triangular component. The luminance of the target triangles were 1/4, 1/2 and 3/4 the luminance of the reference element. The results are presented in Fig 7-6, and show that $T_{\frac{1}{2}}$ values are greatest when the target luminance was closest to the

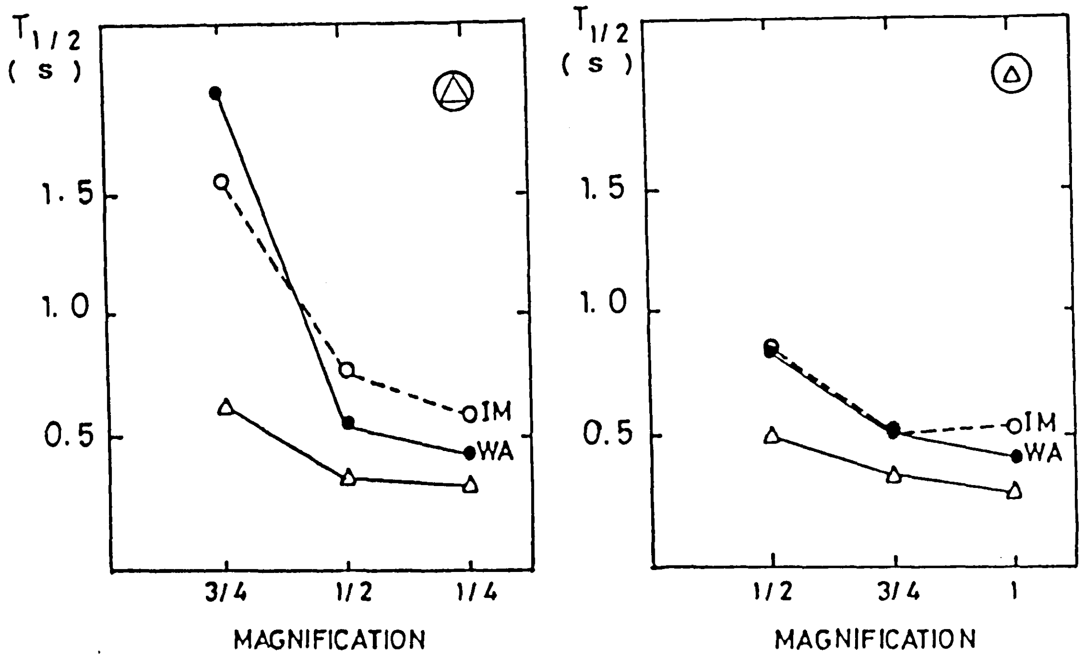

FIG. 7-5. Magnification measurements with complex elements. The reference elements are illustrated in the upper right corner and $T_{1/2}$ is plotted against the magnification of the target, the triangle within the circle, for 40 reference elements.

(O) Data for subject IM with circles.
(●) Data for subject WA with circles.
(Δ) Data for subject WA without circles.

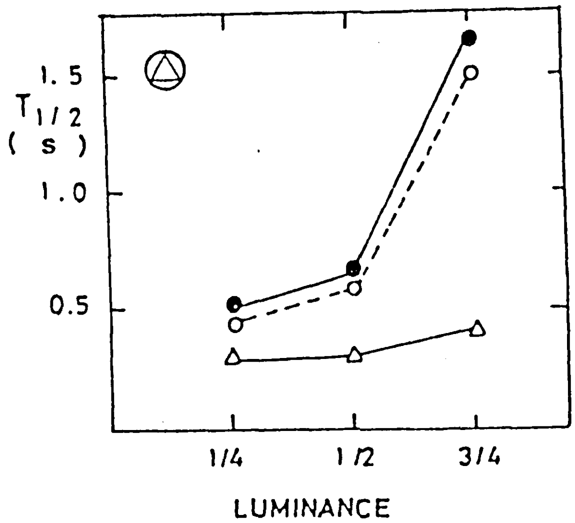

FIG. 7-6. Discrimination of luminance difference with complex patterns. The reference field consisted of 40 elements of the kind shown in the upper left corner. The triangular component of the target differed in luminance from the reference triangles, which were of relative luminance 1.0. $T_{1/2}$ is plotted against the relative luminance of the triangular component of the elements.

(○) Data for subject IM with circles.
(●) Data for subject WA with circles.
(Δ) Data for subject WA without circles.

reference field. $T_{\frac{1}{2}}$ values for these elements without circles are also plotted and are much lower than with circles and are similar for all levels of luminance. Thus the surrounding circle also makes discrimination of luminance more difficult.

7.4.4. Measurements of Shape Discrimination:

In this group of experiments, the targets differed from the reference elements only in their shape, and all these shapes were set inside a circle. The various elements used in these measurements are illustrated in Fig 7-7, in which are plotted the experimental data. For those in Fig 7-7a, $T_{\frac{1}{2}}$ values are much greater when the elements are surrounded by circles, but the effect is much less marked in Fig 7-7b. The targets of Fig 7-7a have the same general orientation as the reference elements, whereas those of Fig 7-7b differ markedly in all aspects. Thus even simple pattern discrimination can be influenced by the addition of a surrounding circle to the element.

7.5. Conclusion:

This preliminary study has demonstrated that with complex elements, discrimination of all stimulus parameters examined is slower than with simple elements. In these experiments, the elements were made more complex by the addition of a surrounding circle, and the data of Fig 7-1 suggest that it is enclosure of the elements by the surrounding circle which causes discrimination to be more difficult. Clearly, this conclusion needs to be confirmed by other experiments with different types of elements.

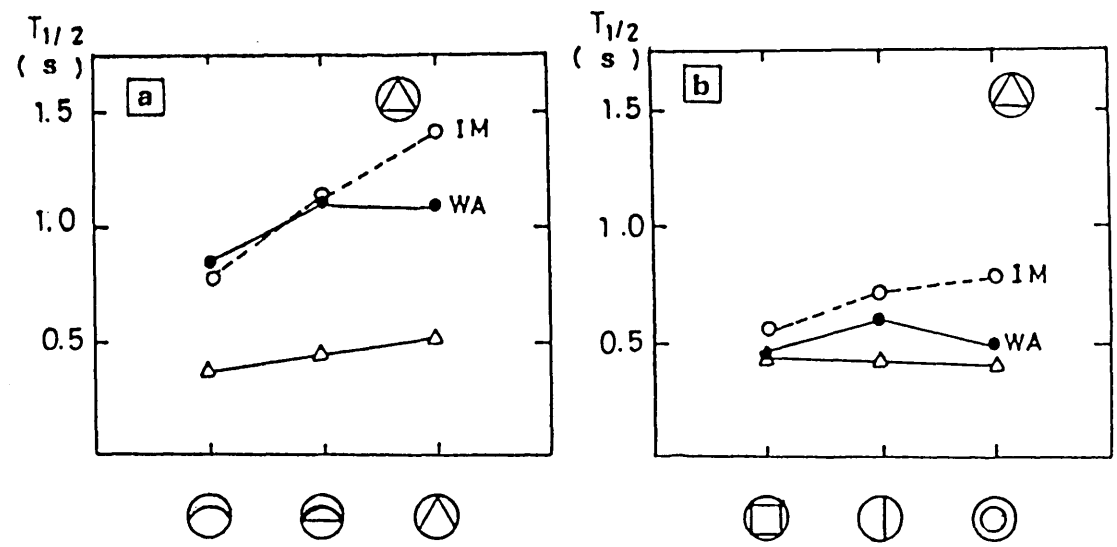

FIG. 7 – 7. Pattern discrimination with complex elements for 40 reference elements, of the kind illustrated at the top right. The targets are plotted along the x-axis, and $T_{1/2}$ values along the y-axis. Data for two subjects:

(O) Data for IM with circles.
(●) Data for WA with circles.
(Δ) Data for WA without circles.

CHAPTER EIGHT

Chapter Eight

Conclusion

The principal results obtained in this investigation are summarized below, and in most cases refer to all classes of targets investigated (lines, squares or triangles).

8.1. The Effect of Field Complexity on Detection of a Single Target (Chapter Three):

Discrimination times for a single target in a complex reference field of mixed orientation or magnification is found to be affected by the complexity of the reference field. Discrimination of the target orientations or magnifications used in this study in a simple reference field, consisting of a multiple of a single class of element, is achieved by parallel processing (Javadnia and Ruddock, 1988a).

For fields which consist of two classes of reference element, the response times, $T_{\frac{1}{2}}$, are greater than for fields made of either component. In almost all cases, the values of $T_{\frac{1}{2}}$ increase with the number of reference elements, N, that is, discrimination is achieved by serial processing (e.g. Fig 3-4, 3-5, 3-12, 3-14, 3-23, and 3-27) even if each component of the reference field, when used alone, gives parallel processing. Thus the tuning of the discrimination mechanisms for orientation or magnification is much coarser than is observed in studies with simple reference fields consisting of one class of element.

The interaction between orientations extends over some 25-30 deg. for lines and over all angles for square and triangular elements. This compares with values of <10 deg. for a single class of reference element (Javadnia and Ruddock, 1988a). Similarly, for magnification, the interactions occur for reference elements which cover most of the linear magnification range (e.g. of size 83% and 33% Fig 3-18, 3-21 and 3-25), whereas for simple fields it is restricted to ≤10% change (Javadnia and Ruddock, 1988a).

The exceptions to these general findings occur when the target lies outside the range of orientation or, especially, magnification covered by the reference field, as is illustrated by Fig 3-19 for lines, Fig 3-22 for triangles and Figs 3-27, 3-29 and 3-31 for square elements.

8.2. <u>The Effect of Contrast Polarity and Colour Differences on Discrimination of Orientation and Magnification (Chapter Four):</u>

When two classes of reference element are distinguished by contrast polarity, as well as by orientation (or magnification) there is a reduction in $T_{\frac{1}{2}}$ values relative to values obtained when both classes have the same contrast polarity as the target. The $T_{\frac{1}{2}}$ values are, however, greater than when either class of reference element is used alone (e.g. Figs 4-24 to 4-28 for orientation and 4-30 to 4-33 for magnification). This effect is shown more clearly with low contrast measurements than for high contrast targets (e.g. Fig 4-24b compared with 4-26a and 4-25b compared with 4-26b for triangles and 4-27a compared with 4-28a and 4-27b compared with 4-28b for square elements in orientation discrimination).

When two classes of reference element are distinguished by colour as well as by orientation (or magnification) there is a reduction in $T_{\frac{1}{2}}$ values relative to those found when both classes have the same colour as the target. This was established for red/green and yellow/blue combinations of opponent colours. The values of $T_{\frac{1}{2}}$ for the mixed colour reference fields are, in most cases, greater than those for a reference field composed of a single class of element.

Similar results for colour differences are found when the elements are embedded in an equiluminance surround, i.e. red/green elements on yellow background and blue/yellow elements on a white background. It is concluded that luminance signals do not contribute significantly to the effects observed with the mixed colour reference fields.

8.3. Interactions Between Orientation and Magnification (Chapter Five):

Measurements of orientation discrimination made with two classes of reference element, which differ both in orientation and magnification, show that the mechanisms which mediates orientation discrimination are sensitive to magnification. Thus if one of the two classes differs significantly in size as well as orientation from the other, with the target matched in size to one class of reference element, $T_{\frac{1}{2}}$ values are reduced relative to values found with both classes matched in size. The size tuning characteristics of the orientation mechanism have been measured in full (Fig 5-7 and 5-10a&b).

Conversely, the mechanism responsible for discrimination of magnification appears to be almost insensitive to orientation. Thus, with two classes of reference elements which differ significantly in orientation as well as in magnification, the $T_{\frac{1}{2}}$ values are very similar to those found when the two have the same orientation. This has been measured in detail (Fig 5-15 and 5-16) and results of these measurements indicate that the mechanisms responsible for magnification discrimination are relatively insensitive to differences in orientation (Fig 5-16).

8.4. Hierarchy of Discriminations:

The conclusions reached in the previous three sections can be summarized in a diagram (Fig 8-1) representing the different stages of visual processing corresponding to the different discrimination mechanisms examined in the Thesis. Thus, the image is divided first into colour and monochromatic representations and the latter is divided into the two contrast polarities. The colour channel divides into its distinguishable colours, and the four channels shown in the figure reflect the divisions into four opponent colours, but finer discriminations are probably made (e.g. Wright, 1929). Discrimination of magnification gives rise to a number of size channels, the number of which has not been determined, and these are followed by orientation discrimination channels.

Note, this model refers to the simple geometrical targets used in this study, and not necessarily to finer spatial discriminations.

8.5. Discrimination of Luminance (Chapter Six):

Measurements for luminance discrimination show that when discriminating a target on the basis of luminance from a simple reference field, $T_{\frac{1}{2}}$ values are minimum when the target differs in relative luminance from the reference element by ≥±30%. When the relative luminance of the target differs by ≤±30% $T_{\frac{1}{2}}$ values increase, becoming infinite when the luminances match (Figs 6-2 to 6-6). The critical value of about 30% is significantly greater than the 10% luminance difference required for minimum $T_{\frac{1}{2}}$ values, when spatial discrimination are made with the target and reference elements at equal levels above a uniform background (Javadnia and Ruddock, 1988a). Luminance discrimination forms an independent discrimination parameter, not represented in the summary diagram (Fig 8-1).

In a second set of experiments, orientation discrimination was measured for two classes of reference element which differed in both orientation and luminance, the target being matched in luminance to one of the two reference classes. In this case, $T_{\frac{1}{2}}$ values showed no consistent dependence on the relative luminance difference between the two classes of reference element (Fig 6-7 to 6-9), which implies that the orientation discrimination mechanism is relatively insensitive to differences in luminance. A similar result is also observed for discrimination involving colour differences, both with complex reference fields (Figs 4-3 to 4-5) and with simple reference fields represented under equiluminance differences (Javadnia and Ruddock, 1988b).

8.6. <u>Discrimination of Complex Patterns (Chapter Seven):</u>

A few data were presented in which the effect of introducing more complex patterns was examined. The results indicate that enclosing the geometrical patterns in a circle makes discrimination of the orientation and magnification more difficult, because

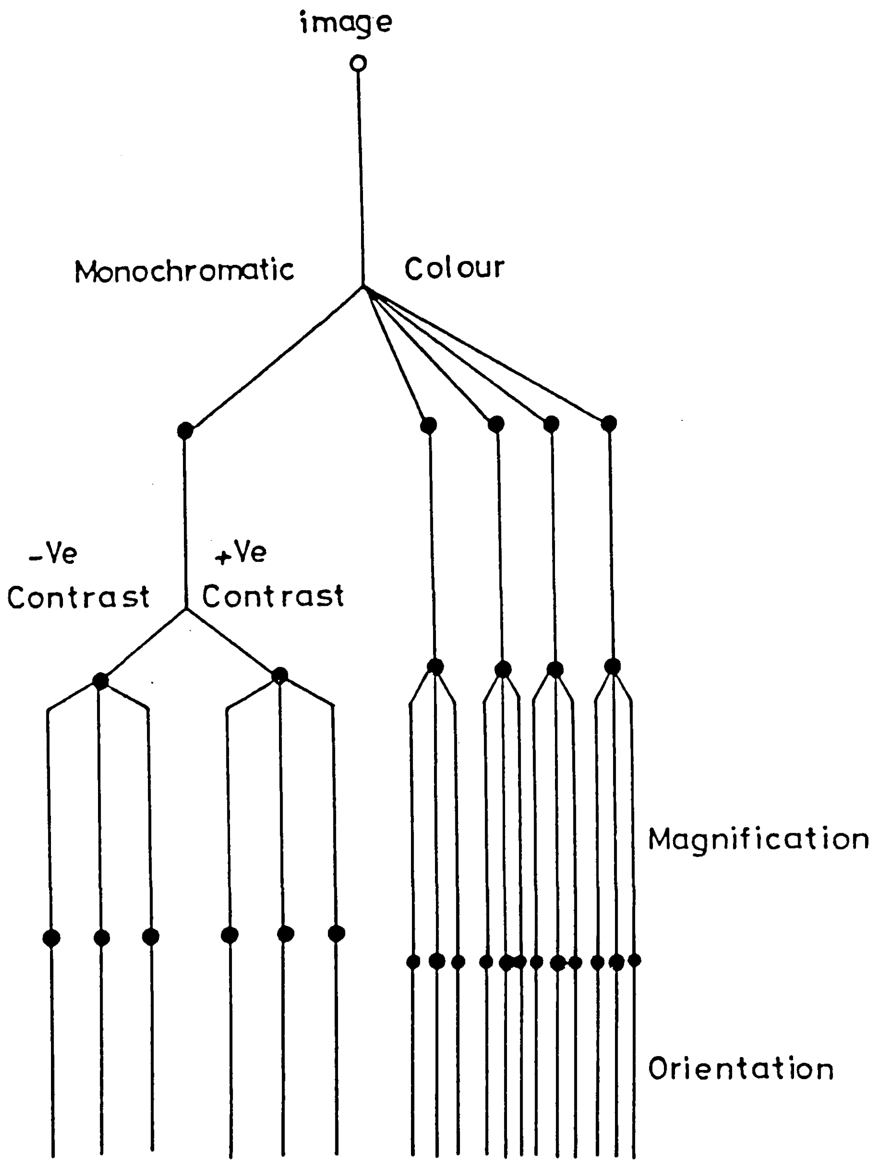

FIG. 8 - 1 . Schematic representation of the stages of visual processing, for stimuli at fixed luminance level. The constrast variations are regarded as perturbations around a constant, average illumination. The number of channels used to illustrate the processing of colour and magnification has no particular significance.

$T_{\frac{1}{2}}$ values increase (Figs 7-1a&b, 7-2, 7-5, 7-6 and 7-7). This is not the case if circles intersect the elements, even though the patterns are in some ways more complex than when the circles surround the elements (Figs 7-1c&d). There are clearly a variety of experiments which could be performed to elaborate on this finding.

In undertaking this research I wished to investigate the parametric factors which influence the discrimination of spatial parameters, with particular reference to simple geometrical patterns. The principal findings are summarized above and are represented by the schematic network shown in Fig 8-1.

Appendix

In Chapter Four experiments were performed with equilateral triangles for reference and target elements of the same size but with the target distinguished by orientation. The reference elements consisted of two classes of coloured triangles, red (R) and green (G), which differed in orientation. One of them was set at constant luminance (relative luminance=1) and the other set at a series of different luminance levels. The targets always had the same colour and luminance as the fixed reference elements but varied in orientation from both classes. The data presented in this appendix show the results obtained with the different combinations of orientations and relative luminances of the two colours.

It is clear from these results that when the difference in orientation of the target from the reference elements is large, the effect of the introduction of the second target, which is different in colour from the target, is very small. If the target orientation falls between the two reference elements (0 deg. and 30 deg.), however, the effect of the second reference, which has a different colour and relative luminance from the target, is noticeable and the discrimination becomes serial. The important point, however, is that the relative luminance of the two classes of reference element have little influence on the results.

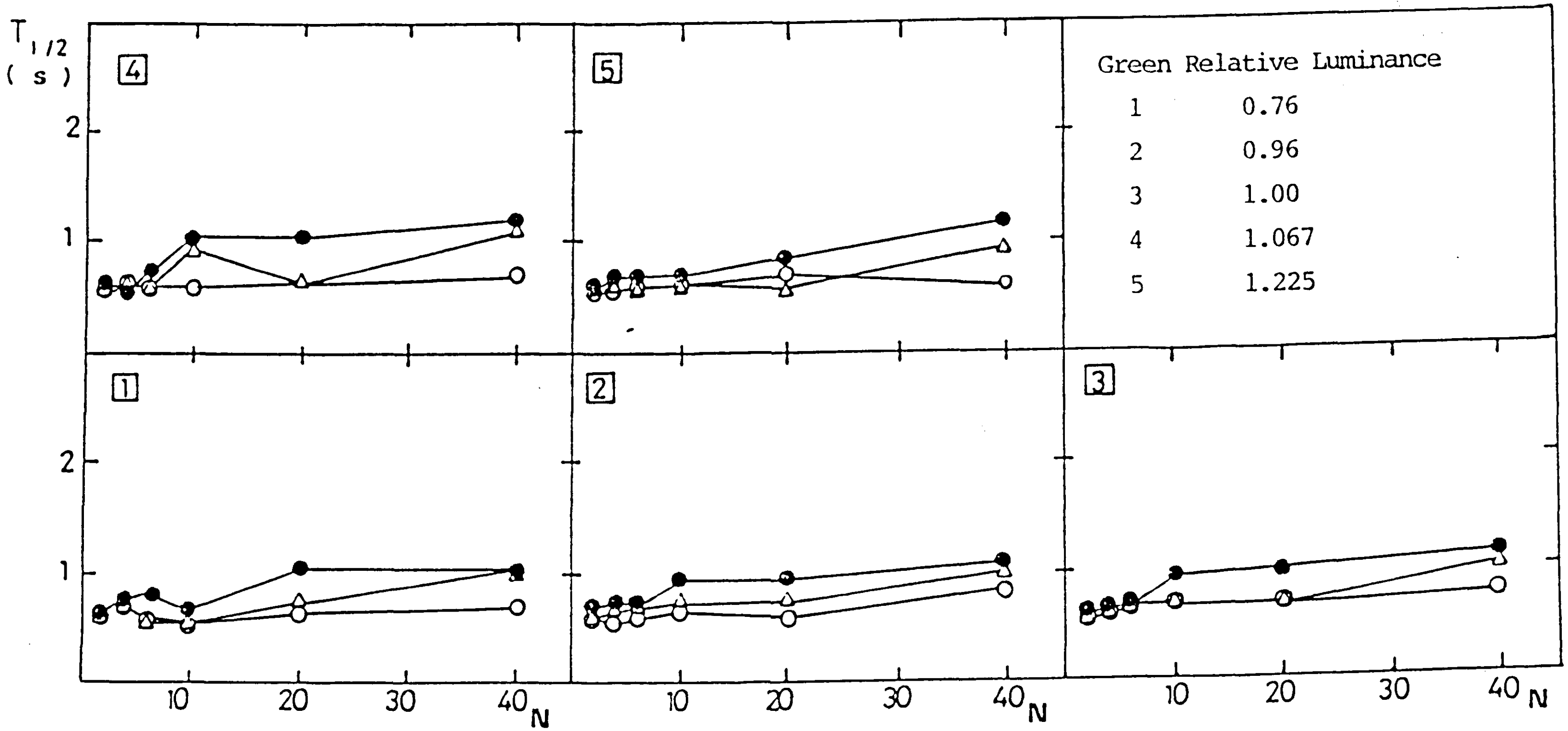

FIG. A-1. The effect of relative luminance on the effect of discrimination of orientation with reference fields consisting of mixed orientation and colour. The reference field consisted of red elements, ▲ , of relative luminance 1.0, and green elements , ▼ , the relative luminance of which changed for each data set as defined at the top right. Data for red targets, at relative luminance 1.0, and orientation 15° (●); 30° (△) and 90° (○).

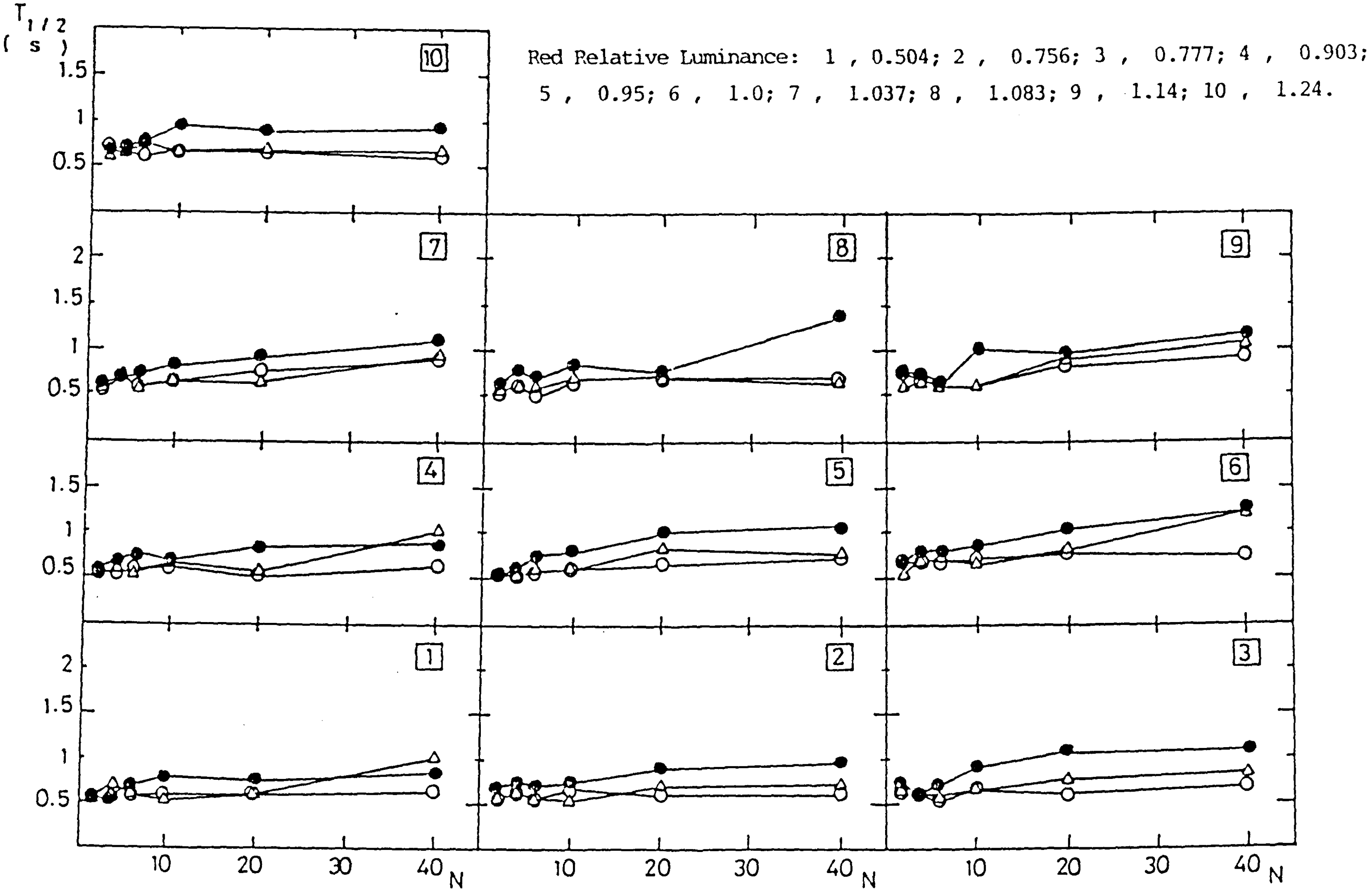

FIG. A-2. As Figure A-1, but for green targets and reference elements ▲ green and ▼ red, with relative luminance 1.0 for the green element and varying for the red element.

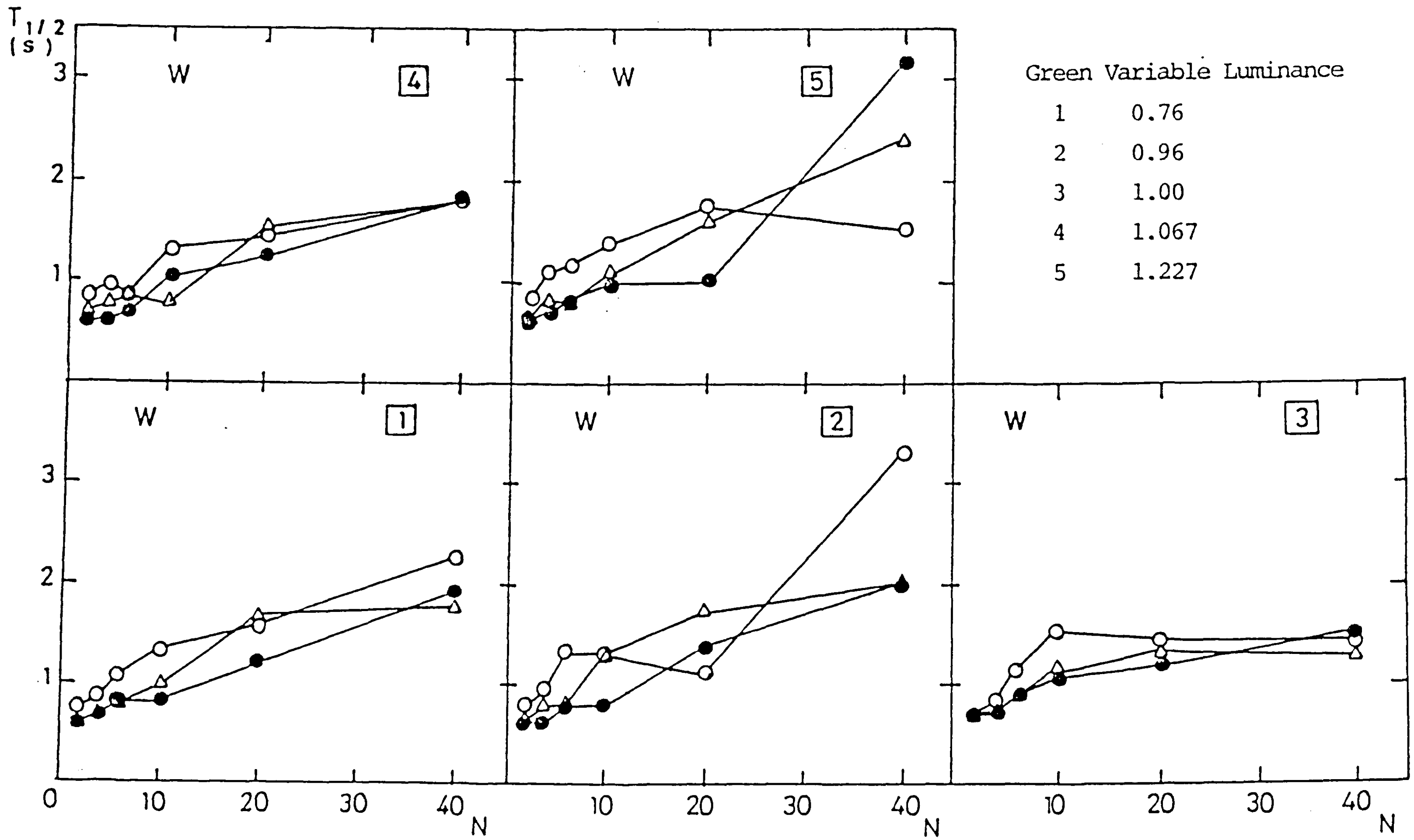

FIG. A-3. As Figure A-1, but for reference element red ▲ and green ◀ . The luminance of the latter varied as defined at the top right. The red targets were oriented, 6° (○), 12° (△) and 18° (●).

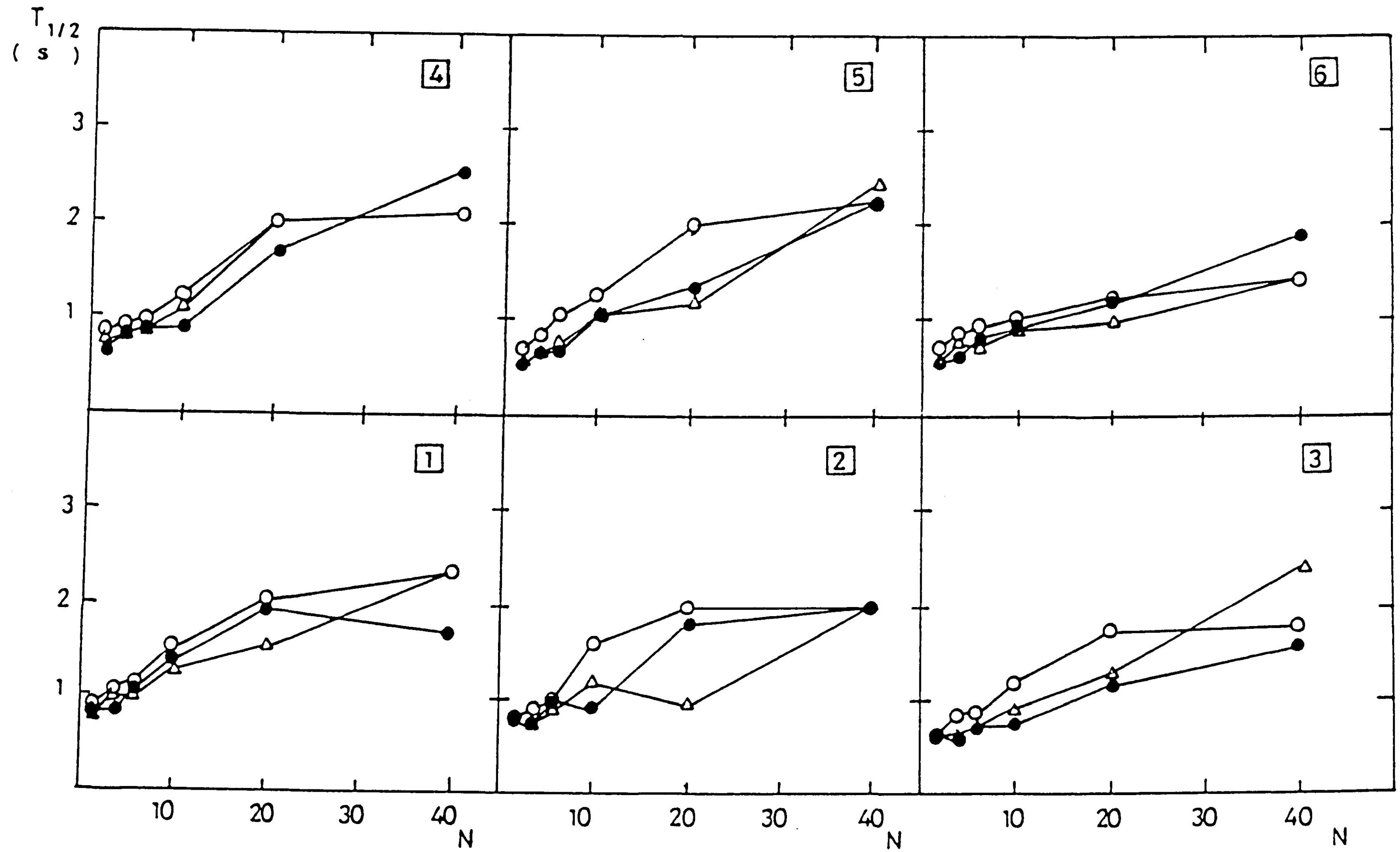

FIG. A-4. As Figure A-3, but for green targets and the red and green reference elements reversed. The red relative luminance: 1 & 6 1.0 (for two subjects); 2, 1.028; 3, 1.043; 4, 1.06; 5, 1.098.

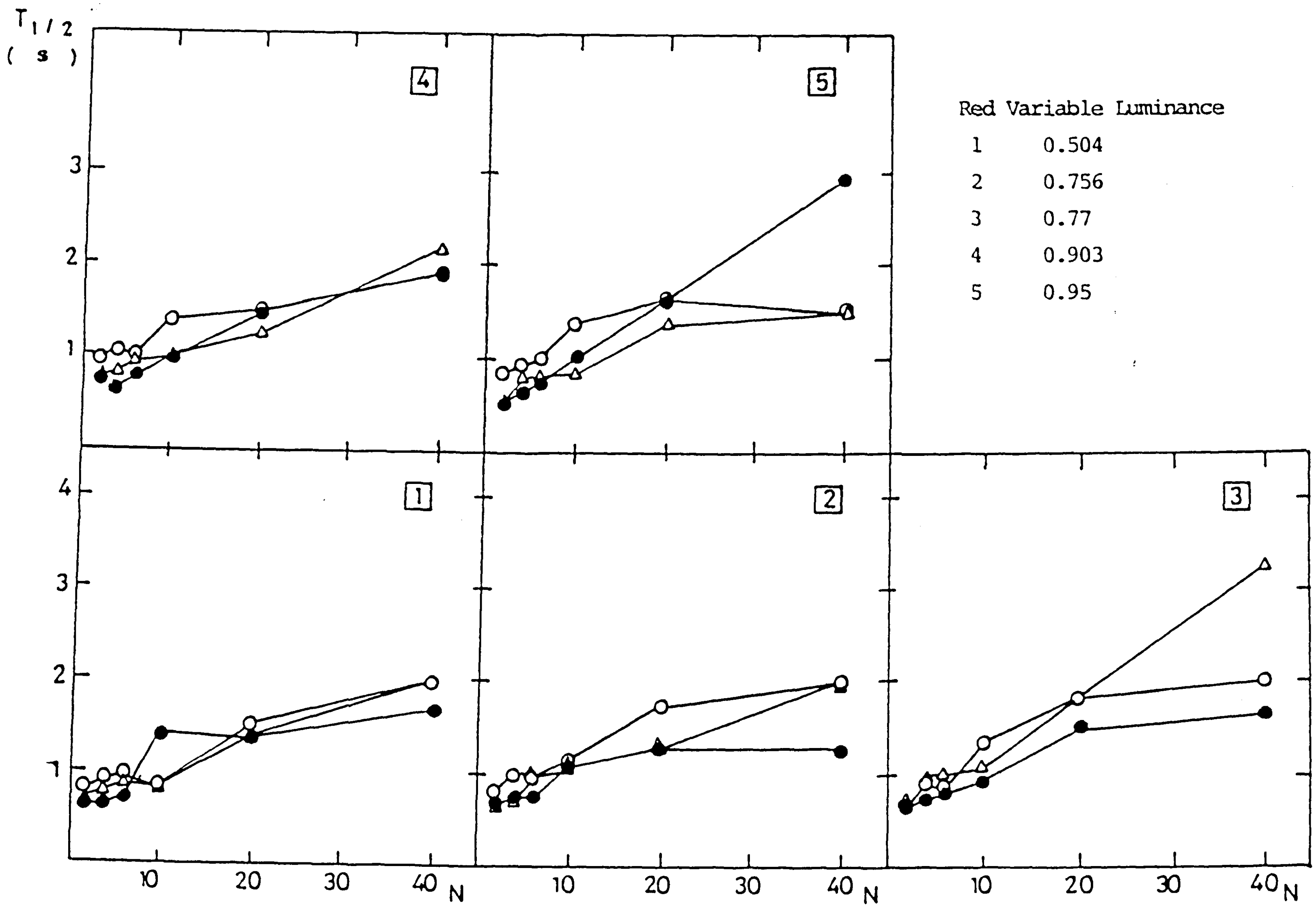

FIG. A-5. As Figure A-4, but for different luminances of the red elements.

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Functional mapping of stimulus colour in a human subject suffering a central visual defect

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The multiple maps of the visual field found in the striate and pre-striate cortex of the macaque exhibit selective responsiveness to different stimulus parameters (Zeki, 1978, 1980). Evidence for such organization in man is derived primarily from selective losses of visual function associated with disturbance of the central pathways. We present data for a single subject, M. W., who has normal achromatic vision but exhibits grossly abnormal responses to coloured and particularly red stimuli, as is illustrated by Fig. 1 (*a*). The extended image of the red target appears 'steely-grey' and targets located within the image are not detected. The spreading inhibitory action of red stimuli has been demonstrated objectively by increment threshold measurements (Bender & Ruddock, 1974; Hendricks, Holliday & Ruddock, 1981).

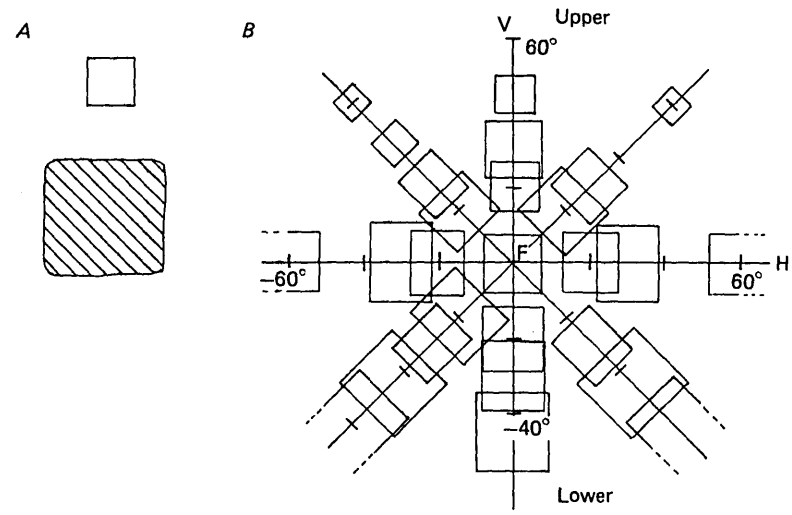

Fig. 1. *A*, the lower hatched area is M.W.'s sketch of the upper stimulus, a red square with CIE coordinates $x = 0{\cdot}505$; $y = 0{\cdot}284$; $Y = 23$. *B*, the image produced by the same red square, presented at different points (denoted by crosses) in the visual field. H, horizontal meridian; V, vertical meridian; F, fixation point. Subject M.W.

We have determined the apparent size of images generated at different locations by a 6·2 deg square red patch. The results (Fig. 1 *B*) demonstrate grossly non-uniform magnification over the visual field, and both psychophysical and evoked potential measurements indicate that the distorted images arise at post-striate level.

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Parallel and Sequential Processing in Visual Discrimination of Simple Geometrical Patterns

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Abstract

This paper describes an experimental investigation of pattern discrimination by the human visual system. Observers were asked to detect a single target element, embedded in a random array of identical reference elements, and in this study, the target was differentiated from the reference elements by orientation or magnification. The dependence of the response time for detection of the target on the number, N, of reference elements provided a measure of the extent to which the target parameters could be discriminated by parallel operations, without sequential scanning of the elements. The results establish that, with the exception of certain classes of elements, response times are essentially independent of N, that is, the targets can be discriminated without sequential scanning of the field. The exceptions occur when the target parameters differ by only a small amount from those of the reference elements, or when the elements are structurally ill-defined. It is shown that a subject with visual form agnosia suffers a severe loss of capacity for parallel discrimination.

In a second set of experiments, the elements were differentiated from the background field by colour and/or luminance. It is shown that normal capacities for the discrimination of magnification or orientation are retained when the elements are at equi-luminance with the background, and are distinguished from it only by colour contrast. Data for a subject with a congenital red–green colour vision defect establish that under these conditions, the responses are dependent on the physiological mechanisms of colour vision.

Introduction

The discrimination and recognition of everyday visual scenes requires the analysis of multiple image features and in the main, this is performed without serial scanning of the stimulus. Thus the visual system operates at least partially as a parallel processor of the retinal image and we describe an investigation of this capacity in man. The organization of the visual pathways provides some evidence as to the way in which parallelism is achieved. The visual field is mapped, topographically, on to the different neural stages of the pathways, and neurones with common response characteristics are distributed over the various field representations. Thus the functions performed by neurones such as retinal ganglion cells and orientation-sensitive cells of the striate cortex are replicated all over a distributed image. A further significant feature of the visual pathways is the multiple representation of the visual field in the striate and pre-striate cortex. The electrophysiological properties of single neurones suggest that the processing of different stimulus parameters, such as colour and orientation, is distributed between these different areas (Zeki, 1978).

Psychophysical methods have been applied in the investigation of corresponding functions for human vision. Julesz and his co-workers have identified certain features of textured spatial patterns, called "textons", which can be discriminated in "pre-attentive" vision, without scanning of the visual field (Julesz, 1980, 1981). The capacity to discriminate or to detect co-jointly different features of the image has been investigated in reaction time experiments employing multi-element stimuli (Treisman, 1983). In the study to be described, we have investigated both these aspects of visual performance, using a reaction time measurement of visual discrimination. The methods have been described elsewhere (Ike *et al.*, 1987), and have found application in the study of abnormal as well as normal visual function (Ike and Ruddock, 1984, 1987; Bromley *et al.*, 1986). Results for abnormal function provide important clues about visual organization and data for two subjects with visual dysfunctions are included in this chapter.

Methods

Reference picture elements were drawn interactively on a visual display screen (Microvitec Cub) and were stored for multiple replication, together with a target, drawn separately and also stored. Each displayed pattern consisted of a single target element and a chosen number, N, of identical reference elements from which it was to be discriminated. The positions of the elements changed randomly from presentation to presentation, in such a way as to eliminate overlap between any elements (Fig. 1a), and the target was selected at random from a set of four, including a "null" target which matched the reference elements. Each set of targets was distinguished from the reference elements by a single parameter, such as relative orientation, and the value of the parameter was different for each target (Fig. 1b). In some experiments, it was required that the elements, both reference and target, be differentiated in colour from the background in which they were embedded, as is illustrated in Fig. 1c. In the experiments to be described, the elements were either linear or in the form of equilateral triangles. The line length was in all cases 0.45 deg unless otherwise specified.

In order to respond, the subject pressed one of two buttons, denoting either "target detected" or "no target" and the computer logged the response time relative to the time of pattern presentation. As soon as the subject responded, the pattern was deleted and replaced by a new pattern. One set of measurements consisted of 25 presentations of each of the four targets, making 100 presentations in all. Probability for detection of the target was displayed against the time after onset of pattern presentation and the time for 50% probability of detection, $T_{1/2}$, used to characterize responses for a given target (Fig. 1d). The VDU was calibrated with a teleradiometer and was viewed from 1.75m, to give a screen size of 9.5 deg horizontally by 7.1 deg vertically. Details of the equipment have been given elsewhere (Ike *et al.*, 1987).

In interpreting the data, we attribute values of $T_{1/2}$ which are independent of N to a parallel process, and those which increase significantly with N to a serial process. We assume that if elements have to be examined foveally in order to determine whether or not they differ, the time required to detect the target will increase as the number of reference elements increases.

Subjects

Data are presented for a number of subjects, all of whom wore refractive correction as required. Two subjects suffered visual abnormalities; one, DG, has a congenital **red–green colour** vision defect,

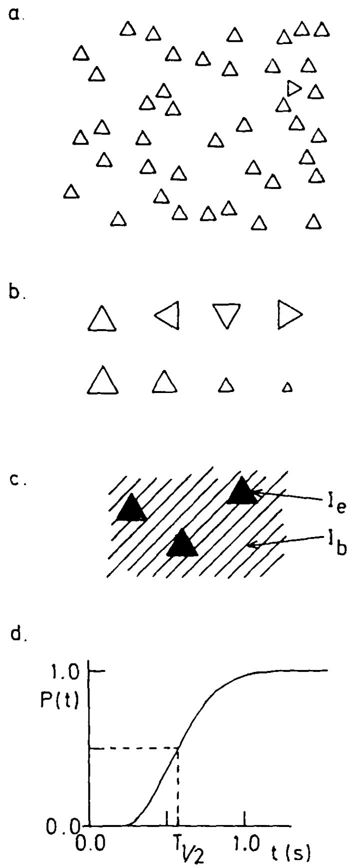

FIG. 1. (a) Typical stimulus field for measurement of orientation discrimination. (b) Set of 4 target elements for discrimination of orientation (upper) and magnification (lower). The first target element is the same as the reference elements and constitutes the "null" target. (c) In colour contrast experiments, the elements, of illumination I_e, were embedded in a differently coloured background, of illumination I_b. (d) A typical set of data; the probability of target detection, $P(t)$, is plotted against the presentation time, t, and the times $T_{1/2}$ at which $P(t)$ reaches 0.5 characterizes the responses.

which was classed as **deuteranomalous** by colour matching methods (Wright, 1946). The other, HJA, has severe pattern recognition problems, classed as visual form agnosia (Humphreys and Riddoch, 1984, 1987), which occurred following a stroke. This subject has normal visual acuity (Snellen acuity 6/6 in either eye) but cannot recognize common objects, including the faces of people well known to him. In addition he has an acquired achromatopsia, but non-visual sensory discriminations are not impaired, and CT X-ray scans show extensive neuronal degeneration in the pre-striate cortex. Extensive measurements on this subject have established that his response times are abnormally long for all visual discrimination measurements, with the sole exception of orientation discrimination for single lines (Bromley *et al.*, 1986). Some of his responses are illustrated in Fig. 2. All subjects were students, aged between 20 and 25 years, with the single exception of HJA, who was 64 years old.

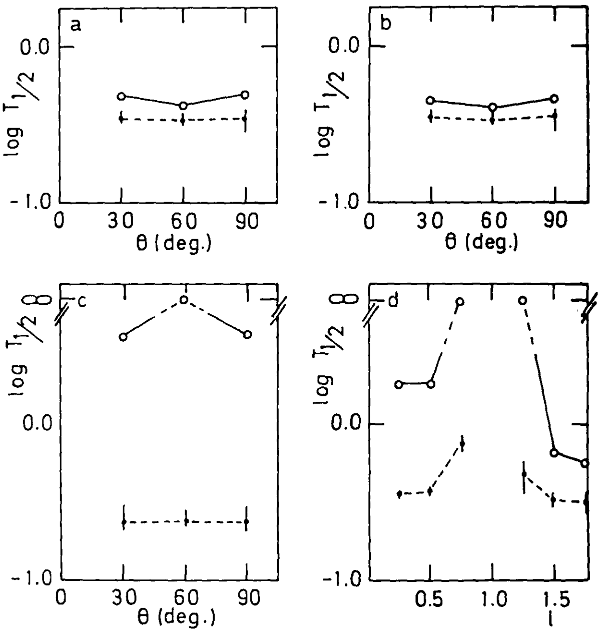

FIG. 2. Values of $T_{1/2}$, in seconds, for several discrimination tasks recorded by the agnosic subject HJA (data given by open circles); closed circles give mean values for 3 normal subjects and bars denote their data spread. (a) Orientation discrimination for straight lines, at angle θ to the reference elements. The number of reference elements, N, was 60. (b) As (a), but for straight "lines" composed of five co-linear spots. (c) As (a), but for equilateral, triangles, with N equal to 20. (d) Magnification discrimination for equilateral triangles, with $T_{1/2}$ plotted against the side length, l, of the target elements, expressed as a fraction of that of the reference elements. N was equal to 20. $T_{1/2}$ equal to ∞ represents failure to achieve 50% detection.

Results

As explained in the Methods section, the raw data consist of probabilities for detection of the target element, $P(t)$, plotted against time, t, and the time $T_{1/2}$ required for 50% probability of detection characterizes the response for a given target. In Fig. 3, $T_{1/2}$ values for detection of orientation are plotted against the number of reference elements, N, each set of values referring to a different geometric shape for the elements. Results are given for straight lines (Fig. 3a), and triangles (Fig. 3b). The $T_{1/2}$ values for different target orientations of each element shape showed similar variations with N, thus they have been averaged in the plots. The difference between $T_{1/2}$ values for different target orientations reflect aspects of pattern discrimination which are not the object of this study, but have been examined in detail elsewhere (Ike *et al.*, 1987). The data of Fig. 3 show that for the majority of targets, the time required for discrimination is essentially independent

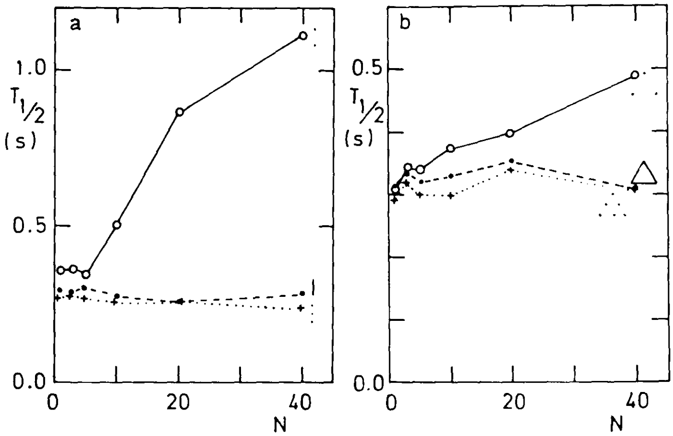

FIG. 3. (a) $T_{1/2}$ for discrimination of target orientation plotted against N, the number of reference elements. The elements were lines or co-linear spots, and the elements to which each set of values refers is plotted to the right of the data. Values of $T_{1/2}$ are averaged for three target orientations, 30°, 60°, and 90° relative to the reference elements, which were orientated vertically. (b) As (a), but for equilateral triangles, with the reference elements orientated △, ∷ and ∴.

of N, the number of background elements, the important exception being when the elements consist of points marking their extremities.

Similar measurements have been made for discrimination of other stimulus parameters and these are illustrated for the case of magnification. Data are given for lines and triangles (Fig. 4a,b) and in this case, the values of $T_{1/2}$ are effectively independent of the number of reference elements, N, for the larger magnification changes, but show a clear dependence on N for the smallest differences.

The results for subjects with normal vision (Figs. 3 and 4) suggest that there is a great deal of parallel processing in discrimination of both magnification and orientation, in that discrimination performance for many targets is essentially independent of the number of reference elements, N. The fact that for certain targets, $T_{1/2}$ increases with the number of reference elements, is discussed later. It should be noted that the average separation of the elements of necessity falls as the number of reference elements increases, and consequently the average separation between the target and the nearest reference element decreases as N increases. Measurements made with just a pair of elements, one reference ($N = 1$) and the target, show that the value of $T_{1/2}$ increases gradually as separation, d, increases over the width of the screen. For example, in one experiment, as d increased from 0.7 deg to 6.5 deg, $T_{1/2}$ rose from 0.35 s to 0.48 s for discrimination of orientation with triangular elements.

The measurements for the aphasic subject, HJA, show a quite different response pattern. In this case, $T_{1/2}$ increases approximately linearly with N for

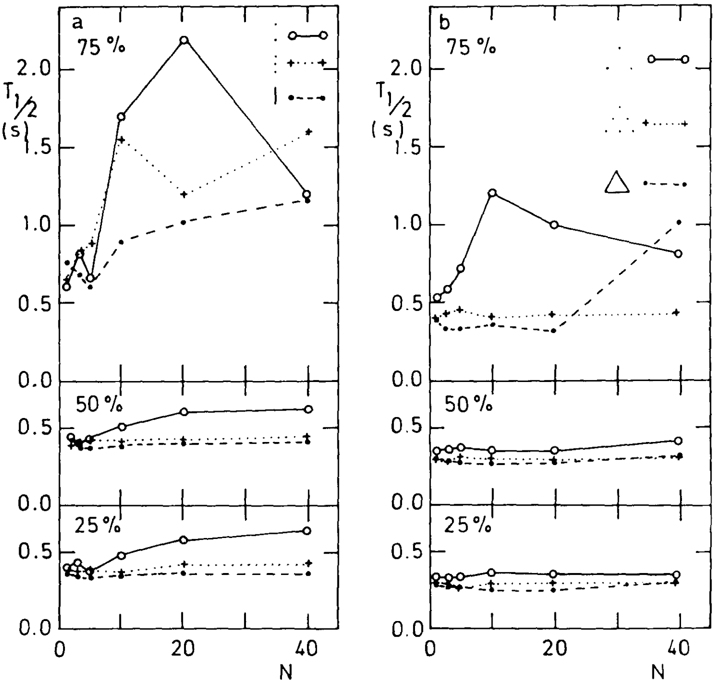

FIG. 4. (a) $T_{1/2}$ for discrimination of target magnification, plotted against N, the number of reference elements. Each data set refers to a different magnification of the target lines, with the target length expressed as a % of the length of the reference lines. Data are given for several different kinds of linear elements, as denoted on the figure. (b) As (a), but for equilateral triangular elements.

orientation discrimination of elements such as Δ (Fig. 5), although in normal vision, $T_{1/2}$ is independent of N for such discriminations.

The experiments designed to determine the simultaneous processing of colour and spatial patterns such as orientation and magnification required measurements of target discrimination against backgrounds of different illuminations. Values of $T_{1/2}$ are plotted against the ratio of the background illumination to that of the elements. Two different background conditions were examined for each spectral composition of the elements, one of which gave colour contrast with the elements and the other, in which the background and the elements were matched in colour, provided simple luminance contrast. Orientation discrimination for triangles is illustrated in Fig. 6a,b and magnification discrimination for the same elements in Fig. 7a,b. The ability to achieve discrimination is sustained through the whole range of illuminations for colour contrast, whereas there is a significant range of luminance contrasts for which $T_{1/2}$ is raised. Similar results were obtained with other colour contrasts, thus it appears that both magnification and orientation can be processed on the basis of colour contrast at equi-luminance level, but requires a significant luminance contrast when no colour contrast is available.

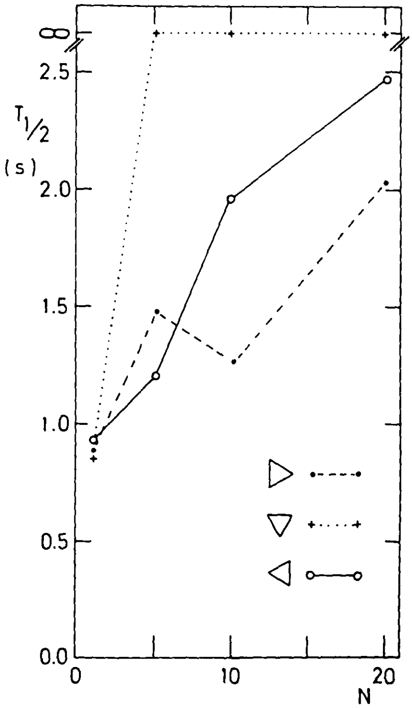

FIG. 5. $T_{1/2}$ for detection of target orientation, plotted against N, the number of background elements. The reference elements were △, and the target orientations are shown on the figure. $T_{1/2} = \infty$ represents failure to achieve 50% detection. Subject H.J.A.

The contribution of colour vision in performing these discriminations is further illustrated by experiments with the anomalous trichomat DG. For "orange" elements embedded in a "red" background, DG fails to discriminate the elements from the background by colour contrast and, correspondingly, his response time, $T_{1/2}$, is raised for a range of contrasts around that at which the elements and background are matched (Fig. 8). Normal subjects, however, use the colour contrast to achieve response times which are essentially independent of the luminance contrast between the elements and the background.

Discussion

The data of Figs. 3 and 4 establish that the visual system can, in many cases, detect a change in stimulus orientation or magnification independently of the number of reference elements from which the target must be distinguished. Thus, these parameters can be distinguished by parallel processing, without recourse to scanning of the field. Certain targets cannot, however, be discriminated in this way and for these the response times $T_{1/2}$ increase as the number of reference elements, N, increases. It is of interest to examine the reasons why non-parallel

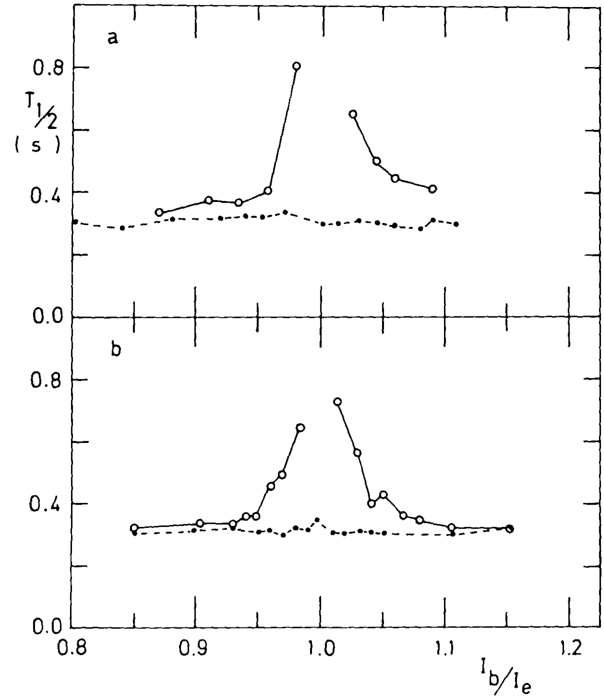

FIG. 6. $T_{1/2}$ plotted against the ratio of the background illumination. I_b, to that of the elements, I_e. (a) Data for "green" triangular elements (C.I.E. co-ordinates X = 0.303, Y = 0.404) on a "red" background (X = 0.602, Y = 0.354), denoted by full circles, and for the same "green" elements on a matching background (open circles). The targets were distinguished by orientation at 30°, 60° and 90° from the 40 reference elements, and $T_{1/2}$ values are averaged for all three orientations. (b) As (a), but for "yellow" elements (X = 0.435, Y = 0.49), on a "blue" background (X = 0.148, Y = 0.078), denoted by full circles and for the "yellow" elements, on a matching "yellow" background, denoted by open circles.

processing is necessary in these cases. For orientation discrimination involving two similar classes of element, : and ∴, $T_{1/2}$ increases rapidly as N increases (Fig. 3), and in making such discriminations, the observers found it necessary to scan the VDU screen, in order to detect the target. One possible explanation of this result is that lines must be defined by a minimum of three co-linear points for orientation discriminations. The subjects of these experiments observed, however, that for larger values of N, it became difficult to associate individual image points with any single element, and this, rather than detecting the orientation of lines defined by two points, limited performance. Similar measurements were performed with smaller elements (with point separations of 0.3 deg as opposed to 0.45 deg for the data of Fig. 3), and these gave much clearer definition of elements such as : and ∴ when N was large. Correspondingly, $T_{1/2}$ values were far less dependent on N than those shown in Fig. 3, thus co-linearity defined by three or more image points is not essential for parallel processing.

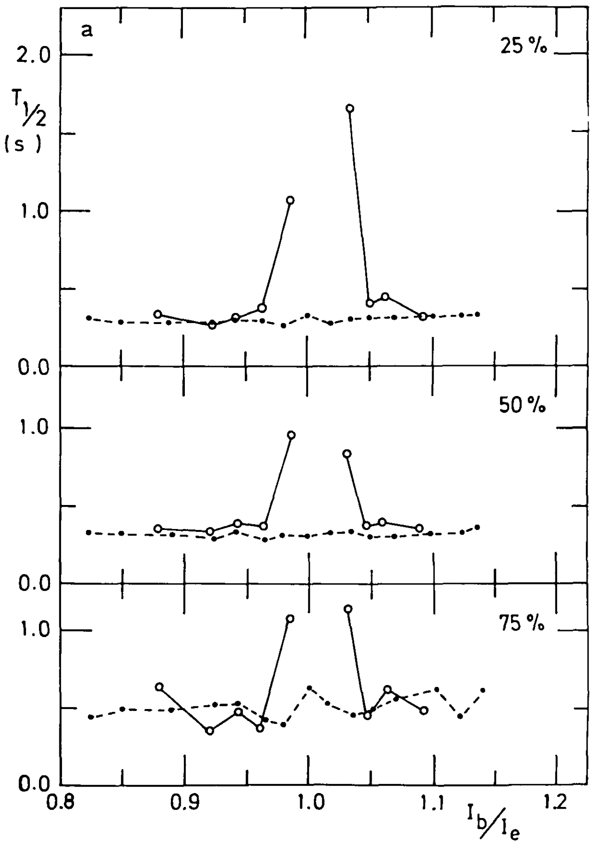

FIG. 7(a) $T_{1/2}$ plotted against the ratio of the background illumination I_b to that of the elements, I_e. The elements were equilateral triangles, and the targets were distinguished by magnification. The percentage values define the side length of the target relative to that of the reference elements. "Green" targets (X = 0.303, Y = 0.604), on a "red" background (X = 0.602, Y = 0.354), denoted by full circles, and on a matching "green" background, [denoted by open circles].

Small changes in magnification could not be detected without scanning of the visual field, and correspondingly, $T_{1/2}$ values increase significantly with N (Fig. 4, 75% target). For larger differences in magnification, however, the data show parallel processing of the image, with $T_{1/2}$ independent of N. Central viewing of the target is necessary for discrimination of fine differences in any spatial parameter and this reflects a general limitation on parallel processing. The precise parametric limits which characterize parallel and non-parallel pattern discrimination are clearly of some interest and need to be established experimentally.

The examples discussed above are exceptions to the general finding that in normal vision, variation in orientation or magnification of simple patterns can be extracted by parallel processing of the retinal image over large areas of the central visual field. The importance of parallel processing is illustrated by the data for

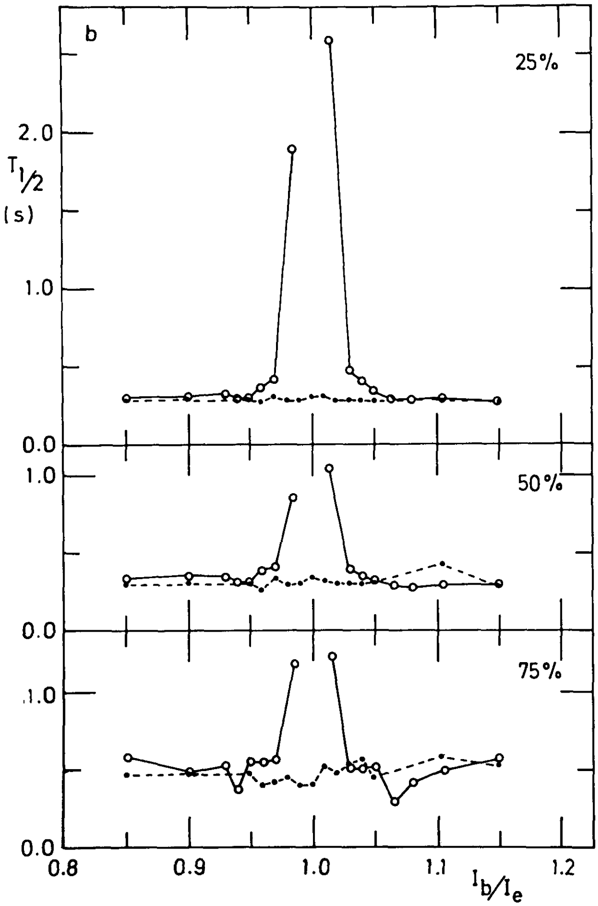

FIG. 7(b) As Fig. 7(a) "Yellow" targets (X = 0.435, Y = 0.490), on a "blue" background (X = 0.148, Y = 0.078) denoted by full circles, and on a matching "yellow" background, denoted by open circles.

subject HJA who, despite having normal visual resolution, cannot recognize everyday objects, although he can sometimes identify components of objects or their photographic representations. He can identify correctly single elements of the visual fields used in this study, but the data of Fig. 5 show that his response times, $T_{1/2}$, increase rapidly with the number of background elements, N, for discrimination of gross differences in orientation. He can discriminate the target in multi-element patterns only by scanning the elements sequentially, no matter by what parameter the target is distinguished from reference elements. The sole exception is discrimination of orientation for single lines, for which his responses are essentially normal (Fig. 2a,b). Thus his abnormal responses are stimulus specific and are not caused by general loss of search capacity or of some other

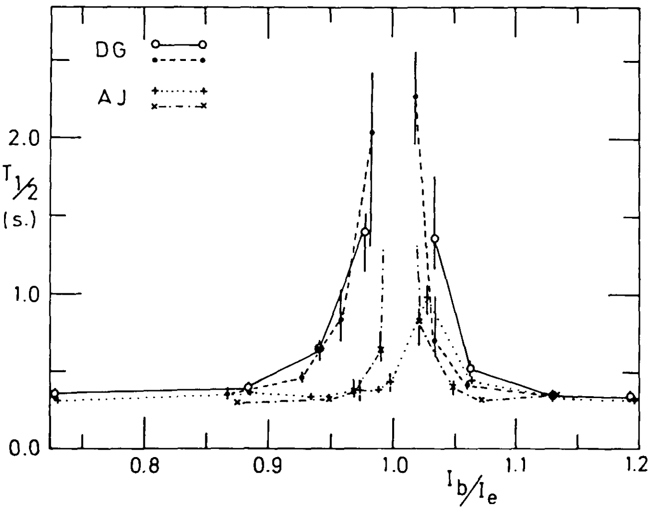

FIG. 8. $T_{1/2}$ plotted against the ratio I_b/I_e, for discrimination of target orientation with forty reference elements. The elements were equilateral triangles, and were "orange" (X = 0.525, Y = 0.415), on a "red" background (X = 0.602, Y = 0.350) or on a matching background. Data for the deuteranomalous subject DG, for "orange" on "red" (open circles) and "orange" on "orange" (full circles), and for the normal subject AJ, for "orange" on "red" (+) and "orange" on "orange" (×).

non-visual function. In this subject, lack of parallel processing for simple patterns is associated with loss of discrimination and recognition for more complex patterns.

The data for colour contrast stimuli (Figs. 6, 7) demonstrate that discrimination or orientation and magnification remains unchanged as the luminance of the background field changes from a level well below to one well above the equiluminance point. In contrast, for luminance contrast, $T_{1/2}$ values are raised significantly over a range of illuminations around the level at which the elements match the background. The data for the deuteranomalous subject DG (Fig. 8) demonstrate that discrimination for the colour contrast fields does not arise from any artefact of the display or of the viewing conditions. For example, luminance perturbations in the field due to chromatic aberration in the eye lens do not enable DG to perform the discrimination task in a normal fashion and, indeed, the very small differences between the spectral characteristics of the two coloured stimuli used in this measurement effectively eliminate chromatic aberration. We conclude that discrimination of orientation and magnification can be achieved on the basis of chromatic signals. This implies that there must be extensive interaction between groups of neurones which signal spatial characteristics and those which signal chromatic characteristics of the retinal image (Zeki, 1978, 1980; Hubel and Livingstone, 1985).

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