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The Spectral Luminance Function for Deflection of Attention

CIE Technical Committee 1-03 recommends the use of a formula, the Ware-Cowan formula, to estimate the luminances needed to give a brightness match between stimuli of different chromaticity. The formula is derived from numerous studies in which verbal judgements of brightness have been recorded. Here we report an attempt to find an aspect of performance that is controlled by brightness rather than by luminance. We measure the deflection of attention to peripheral stimuli by recording the direction of a subject's saccadic eye movement is a situation where a standard light and a test stimulus are in competition. Stimuli subtending 1 deg of visual angle are presented and the direction and latency of the subject's saccade are measured by means of a limbus-tracking infra-red eye-movement recorder. For all chromaticities of the variable digit, the proportion of paired trials on which the subject makes a saccade to the variable target increases monotonically with its luminance. In the case of the three subjects tested, the frequency of saccades is not significantly affected by dominant wavelength. Thus V (λ) is the appropriate spectral luminous efficiency function for the deflection of attention.

Le Comité Technique de la CIE 1-03 recommande l'utilisation de la formule de Ware-Cowan afin d'estimer la luminance des stimuli de différente chromaticité necéssaire pour obtenir l'égalisation de leur luminosité. La formule est issue de nombreuses études dans lesquelles les jugements verbaux de luminosité ont été utilisés. Dans le présente étude nous avons recherché une caractéristique de la performance qui soit dépendante de la luminosité et non de la luminance. Ainsi, nous avond mesuré le déclin de l'attention à des stimuli présentés en periphérie en enregistrant la direction du mouvement saccadique de L'oeil du sujet lorsque qu'une lumière de référence et un stimulus test sont en compétition. Les stimuli d'un degré d'angle visuel sont présentés, la direction et la latence de la saccade du sujet sont mesurées au moyen d'un aculomètre à infra-rouge. Pour l'ensemble des chromaticités de la cible, la proportion des essais pour lesquels le sujet réalise une saccade en sa direction augmente de façon montone avec sa luminance. Néanmoins, pour les trois sujets testés, la fréquence des saccades n'est pas influencée de manière signficative par la longueur d'onde dominante de la cible. V (λ) est donc la fonction d'efficacité lumineuse spectrale appropriée à la description du déclin de l'attention.

Das technische Komitee der CIE 1-03 empfiehlt den Gebrauch der Ware-Cowan Formel um die Leuchtdichten abzuschätzen, die man braucht, um einen Helligkeitsabgleich zwischen Reizen verschiedener Farbarten zu erlangen. Die

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Formel wurde von zahlreichen Studien abgeleitet, in denen verbale Helligkeitsurteile aufgezeichnet wurden. Wir berichten hier über einen Versuch, einen Leistungsaspekt zu finden, der eher durch Helligkeit als durch Leuchtdichte beeinflußt ist. Wir messen die Ablenkung der Aufmerksamkeit peripherer Reize, indem wir die Richtung der sakkadischen Augenbewegungen einer Versuchsperson in einer Situation aufzeichnen, in der ein Vergleichsreiz und ein Testreiz im Wettstreit stehen. 1 Grad große Reize wurden gezeigt, und die Richtung und Latenz der Sakkaden der Versuchsperson wurden mit Hilfe eines Limbus verfolgenden infrarot-Augenbewegungsaufzeichnungsgerätes gemessen. Für alle Farbarten der variablen Ziffer erhöht sich der Anteil der gepaarten Versuchsdurchgänge, in welcher die Versuchsperson eine Sakkade auf das variable Ziel macht, monoton mit ihrer Leuchtdichte. Bei den drei Versuchspersonen ist die Häufigkeit der Sakkaden allerdings nicht signifikant durch die dominante Wellenlänge beeinflußt. Also ist $V(\lambda)$ die angemessene spektrale Hellempfindlichkeit für die Ablenkung der Aufmerksamkeit.

1. Introduction

Lights that are of the same luminance may not be judged equally bright when the subject is asked to make a direct comparison of juxtaposed stimulus fields (KOHLRAUSCH, 1923; KAISER and WYSZECKI, 1978). The discrepancy between $V\lambda$ and brightness judgements is greatest for saturated lights at the two ends of the spectrum. A recent CIE Technical Committee Report (CIE TC 1-03, 1984) recommends the use of the WARE-COWAN formula (WARE and COWAN, 1987) to estimate the luminances needed to give a brightness match between stimuli of different chromaticity. However, no general recommendation is given for when the engineer should take brightness rather than luminance as the appropriate luminous-efficiency function. Apart from verbal judgements of brightness, there do not appear to be any aspects of human performance that are known to be controlled by brightness rather than by luminance.

Here we hypothesize that the deflection of attention to peripheral stimuli might be one aspect of performance that is controlled by brightness rather than by luminance. We have used a modification of the LEVY-SCHOEN paradigm (LEVY-SCHOEN 1956) to test this hypothesis. The direction of a subject's saccadic eye movement was measured in a situation where a standard light and a test stimulus were in competition. In order to tap a more automatic level of response than the normal voluntary saccade and thus one less influenced by conscious intention, we adopted a procedure known as the gap paradigm in the eye-movement literature, in which the central fixation target is turned off 200 msec before the onset of a peripheral target. This arrangement, in contrast to one in which the eccentric target immediately follows the extinction of the central fixation stimulus, is thought to free the subject's attention and allow it to be captured by the novel event. The resulting type of saccade is known as an express saccade and has a latency of approximately 60 ms less than a standard saccade (Fischer and Ramsperger, 1984). A pilot study indicated that the function relating target-directed fixations to luminance was similar in the two cases, but the function was shallower and more noisy in the case of standard saccades. In addition subjects reported that use of the gap paradigm resulted in a more "free flowing" trial and it is therefore this paradigm that has been used in this study.

2. Materials and methods

A 14″ Sony colour display (GVM 1400) was used to display stimuli. The display was internally adjusted so as to reduce the background luminance to less than 0.01 $cd.m^{-2}$ in order to prevent dilution of colours by the background hue. The digital framestore of a visual stimulus generator (Cambridge Research Systems VSG/2) was used to drive the display. Stimulus screens were drawn via a TMS 34010 Graphics processor controlled by the host computer into 1 Mb of video RAM which was paged to facilitate rapid stimulus presentation. The *RGB* outputs to the CRT were produced by triple 8-bit DACs from the pixel data and 8 bit colour look-up table at a rate of 40 MHz, giving a frame rate of 70 Hz and a spatial resolution of 912 pixels per line with 460 lines per screen. The nonlinear relationship between output luminance and input voltage in the display was corrected by use of poly-linear curve fit to perform the γ-correction for the display. The experiment was controlled and the data acquired using a generic 25 MHz IBM AT/386 DX, which limited the analog to digital conversion rate to approximately 2 $ms.channel^{-1}$. Control and calibration programs were written in Borland Turbo C 2.0 running under Microsoft MS-DOS 5.0.

The subject's head was stabilised in the sagittal plane by an chin rest and in the coronal plane by a U-shaped nose-bridge restraint. Pilot studies indicated that this method was as effective in preventing head movement as a dental-wax impression mouth-bite for the purposes of this study. Eye-movements were recorded using a limbus-tracking eye-movement recording system (EMR) (Gauthier and Volle, 1975). The eye was illuminated with infra-red radiation and detectors collected the light reflected from the margin between the (white) sclera and the (dark) iris – the proportion reflected varies as the eye rotates. Vertical and horizontal measurements were taken as the sum and the difference respectively of the transducer outputs. A multifunction input/output card was used to interface the analogue output of the EMR with the computer.

The subject was able to re-centre the system between blocks of trials by fixating on an arrow in the middle of the display and turning the offset control knob on the EMR, until the zero position was set within 1 deg, at which stage the arrow was changed into a cross to indicate that the zero was set. If at any time during a trial the EMR amplifiers were out of range, an audible warning was given and the centering task was presented immediately.

The frequency response of the instrument results in a time constant of 4 msec for the EMR signal.

Subjects were aged 21–24 and had normal colour vision (with refractive corrections by contact lenses in the case of HL) and had an acuity of 6/6 or better on the metric SNELLEN test.

Experiments were performed in a darkened room with a light-proof hood over the screen and the subject. The subject's eye-to-screen distance was 573 mm so that a 10 mm target at the screen centre subtended 1 deg of visual angle. An external keypad (Electrone: Ortek MCK-22 LT) attached to the computer serial port was used for the subjec's manual responses. All keys except 7 and 9 (odd and even responses) and 1,3 (abord block) were blanked off. The subject was asked to use the dominant hand for manual responses. Saccadic latencies were measured using a one-millisecond resolution counter (INTEL 8253-5) in conjunction with the input/output card.

At the beginning of each trial, the subject was required to fixate a small digit at the centre of the computer-controlled colour monitor, and was asked to indicate with a manual response whether this digit was odd or even. After a variable delay of 100–400 ms, the fixation target disappeared. The screen was blanked for 200 ms after which a coloured digit subtending 1 deg. of visual angle appeared at an eccentricity of 7.5° of visual angle from the fixation point. The digit was displaced up or down by a random distance from the fixation point so that it appeared anywhere on either of two arcs on the screen ± 15° from the horizontal, either to the left or to the right of the fixation point. The subject was required to look at one or other of the peripheral digits and, as quickly as possible, indicate its parity by a manual response. The digits used both for the 1° standard and target digits and for the 0.5° fixation task were 7-segment digits, which were designed to be similar to SNELLEN-test digits in their line width to character size ratio giving a dominant spatial frequency of 2.5 cycles.deg^{-1}.

Randomization of the target position helped to avoid the extremely low latencies caused by antipatory saccades found in some studies (FISCHER and RAMSPERGER, 1984). In addition an anti-anticipation routine in the program cancelled any trial and gave an audible warning, if more than 1° of eye movement was measured between the time of the subject's response to the fixation task and the appearance of the stimulus screen 300–600 ms later (see Fig. 1).

On a subset of trials, the same digit was concurrently presented on the other side of the fixation point, at the same eccentricity and at a standard chromaticity (a white of CIE co-ordinates $x = .310$, $y = .316$) and luminance (10 cd.m^{-2}). In trials where the coloured digit was paired with a standard the spatial configuration was symmetrical so that digit pairs were presented on the same raster line and were thus virtually simultaneous. From trial to trial, the coloured digit varied randomly in chromaticity, luminance, and laterality. The subject was required to look at one or other of the peripheral digits and, as quickly as possible, indicate its parity by manual response. The direction and latency of the subject's saccade and the point of fixation at the time of manual response were measured by the EMR. Aχ^2 test was performed after each trial to test whether any significant left-right asymmetry was present in the accumulated data. If a signigicant asymmetry occurred, a corrective routine was triggered which presented dummy single-digit trials, identical in appearance to the main single-digit trials. Data were not collected from these trials, their

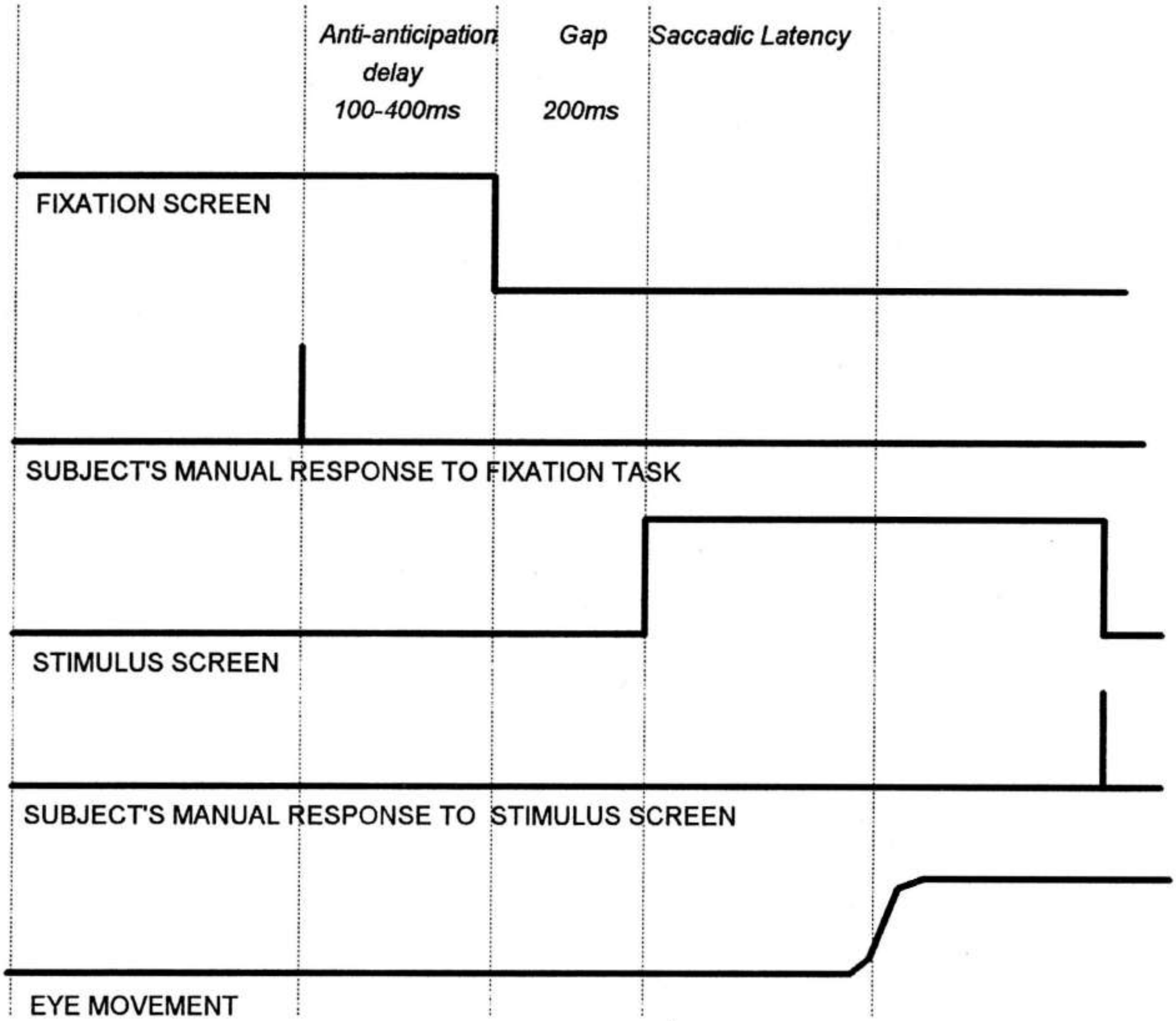

Fig. 1: Temporal aspects of the experimental paradigm used. The trigger for the disappearance of the fixation target is the subject's manual response to the fixation task.

sole purpose being to correct the directional biases that occurred in some subjects.

In addition, subjects were asked to assess subjectively the brightness of the colours used in the study by performing a heterochromatic colour matching task. In this task a pair of digits was presented and the subject was asked to indicate whether the coloured target was brighter than the standard or not. The chromaticities, the target types and their possible spatial configurations were the same as for the two digit stimulus screens in the main task, except for the presence of a 0.1° Illuminant "C" fixation point at the screen centre. Each of the subject's choices were used to adjust one of six staircases – one for each colour – which changed the

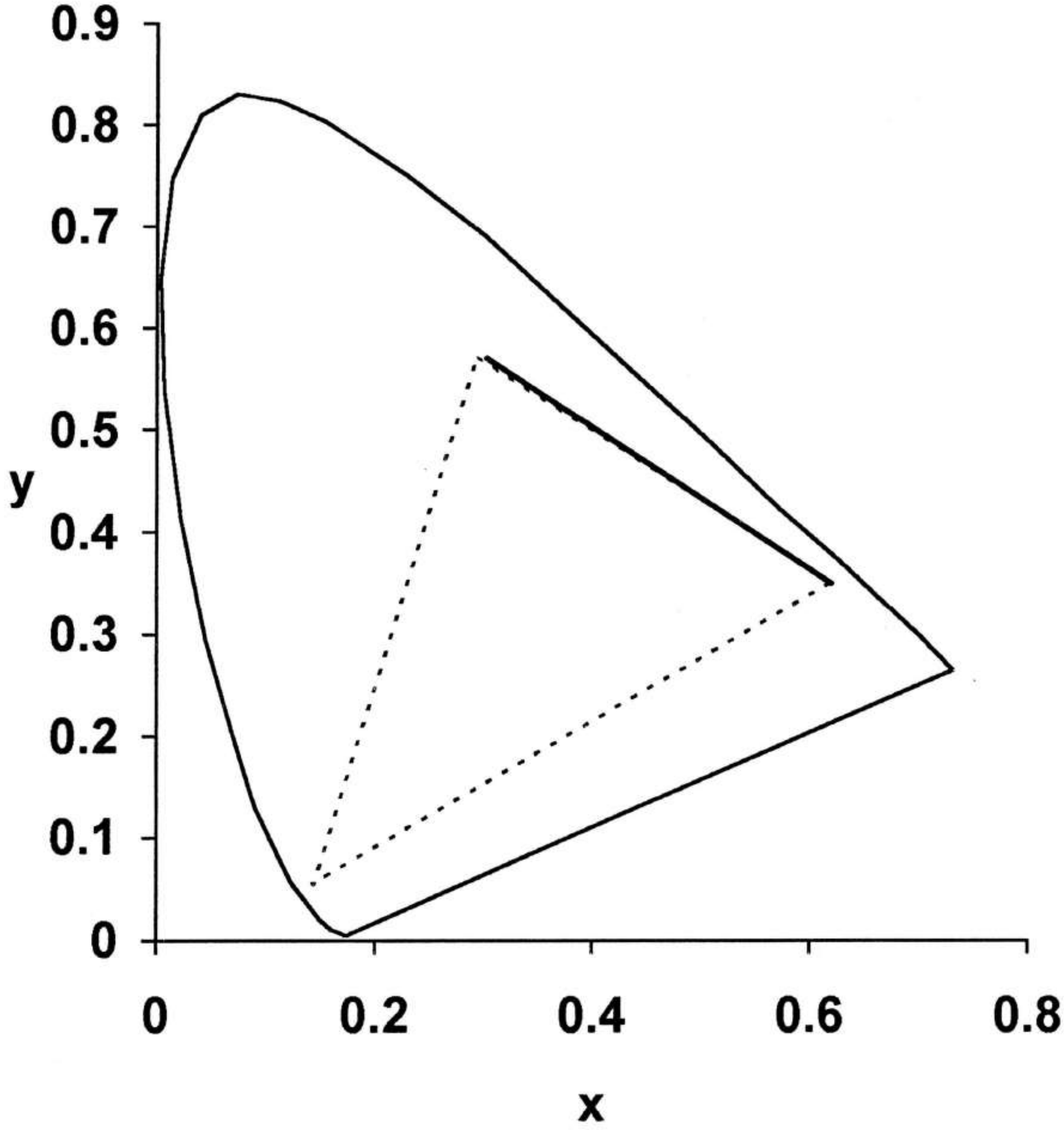

Fig. 2: The line on the CIE chromaticity diagram on which fall the stimuli used in this experiment. The broken lines represents the spectral gamut of the display.

subsequent luminance associated with digits of that colour. All coloured digits started at 10 cd.m^{-2} the same luminance as the Illuminant "C" standard digit. Each colour was adjusted on a separate staircase until 6 reversals of the staircase occurred. Staircase step-size decreased as the reciprocal of the number of reversals on the staircase. On the sixth reversal a match was deemed to have been made and the colour was removed from the block of trials.

Each subject was given the following written instruction prior to making the brightness match: "*Look directly at the fixation point throughout the task. An audible warning will sound if you break fixation. A pair of digits will appear on the screen – one coloured the other white. Press the lower key on the keypad if the coloured digit is brighter than the white digit; otherwise press the upper key.*"

Five colours were used in this study each being a mixture of the red and green guns with the blue gun turned off. The colours corresponded to chromaticities having dominant wavelengths of 547 nm (the green phosphor), 560 nm, 575 nm, 590 nm and 606 nm (the red phosphor). The line in colour space on which these chromaticities are arranged is shown in figure 2.

A chroma-meter (Minolta CS-100) was used to calibrate the display. This instrument was calibrated and characterized against the telespectroradiometer at the *National Physical Laboratory* whose calibrations are traceable to national standards. The chroma-meter was set up on a tripod in darkroom conditions 1 meter from the display. Measurements were taken from a 1° circle at the centre of the screen. The display was turned on and allowed to equilibrate for at least 24 hr before calibration to prevent any effects of warm-up. The serial output of the Minolta CS-100 was attached via the digital ports of the PCLS-35 DS interface to the computer containing the visual stimulus generator that drove the display. A multifunction input/output card (Advance Tech: Enhanced Multi-Lab Card, PCL-812) was fitted into one of the 8-bit slots in the computer to allow the computer to interface with the chroma-meter via the TTL lines. A 5 cm disc was produced in which the input to each of the guns was stepped in turn through 256 equally spaced levels from dark-field to maximum luminance five times and a measurement was made automatically using the chromameter. The median luminance value of each set of five repeats was saved to one of three sequential ASCII files – one for each gun. The phosphor chromaticities were saved only for screens at maximum luminance although the median of five repeats is still used.

3. Results and discussion

For trials in which a single target was presented, the proportion of occasions on which the eye-movement recorder registered a fixation in

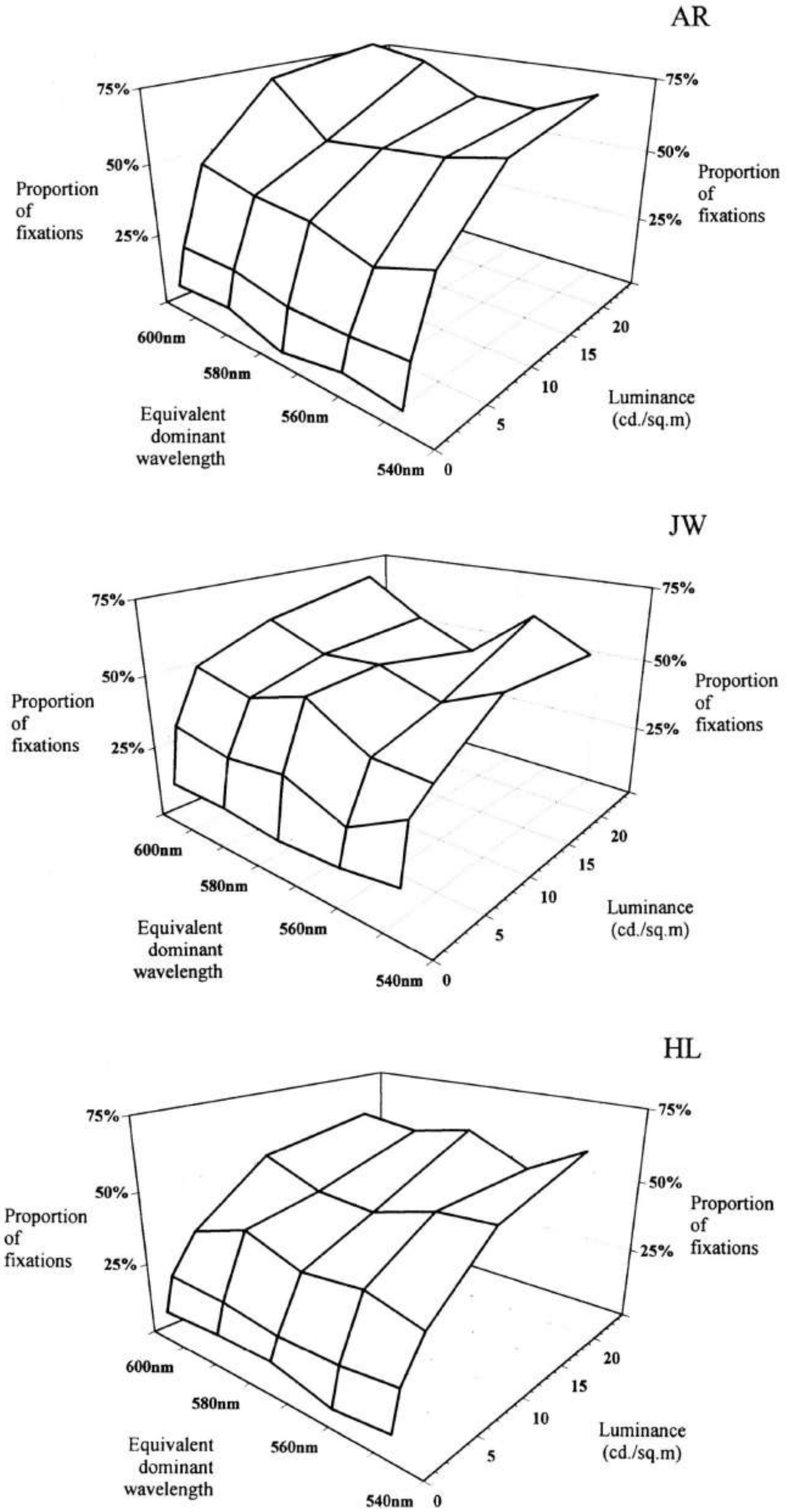

Fig. 3: The proportions of target directed fixations plotted against luminance and equivalent dominant wavelenghts for three subjects. The term equivalent dominant wavelength is used here to denote the wavelenght at which a line drawn through the standard and the target on a chromaticitiy diagram intersects the spectral locus. It ist an "equivalent" wavelength because the stimuli are made up of a mixture of two sources, rather than a single source at the dominant wavelength.

the correct hemi-field was between 97% and 100% for all subjects and for all luminance and chromaticity conditions. This result indicates that the nose-bridge restraint was adequate to secure a high reliability for measurements of gaze direction. This error level is similar to that achieved with a well made dental impression. One possible source of the residual error lies in eye-blinks being picked up as eye displacements but this was unlikely as an out of range warning was sounded, and the task aborted in favour of the fixation task, if the eye-movement recorder registered full scale (equal to 15° or subject's eyes closed) at the time of fixation.

The function relating the relative probability of fixations r to luminance L closely followed a simple logarithmic function such that

$$r = a \log (L) + b.$$

For two subjects the data fitted this function such that $\mathrm{r} > 0.98$ for all chromaticities, whilst for subject JW $\mathrm{r} = 0.863$ for targets of wavelength 575 nm although for all other wavelengths $\mathrm{r} > 0.97$ in the case of this subject.

We define the salience of a light of given luminance and chromaticity as the proportion of fixations it attracts in the competitive trials of the experiment (Fig. 3). We have used a χ^2 method to test the null hypothesis that the salience of lights of a given luminance does not vary with their chromaticity, i. e. with their brightness. The null hypothesis could not be rejected for any of the subjects. Yet the WARE-COWAN formula predicts that the luminance required to achieve equal brightness would vary by over 30% between the brightest (606 nm) and the least bright (560 nm) stimuli, and our own brightness data (Fig. 4) suggest that the effect would be of at least this magnitude in our conditions. In summary, there is no evidence in our data that brightness rather than luminance controls the deflection of attention to peripheral stimuli.

In these experiments we also recorded the latency of the initial saccade. There was no significant difference saccadic latency between the different luminances or colours for any of the subjects ($p > 0.05$). This was true even for the dimmest targets used, the general form of the plot of latency against luminance thus being rather different from that obtained by BOCH et. al. (1984) for *Macaca mulatta.* We also analysed the latencies for different chromaticities in (a) the case where only a single target appeared to the left of the right and (b) the case where the coloured target was in competition with a standard target in the opposite hemifield. The latencies were not significantly different in the two cases.

The mean latencies recorded for our subjects (132 ms ± 4 ms HL, 154 ms ± 4 ms AR, 163 ms ± 4 ms JW) have a small standard error suggesting that our conditions have secured a high proportion of express saccades.

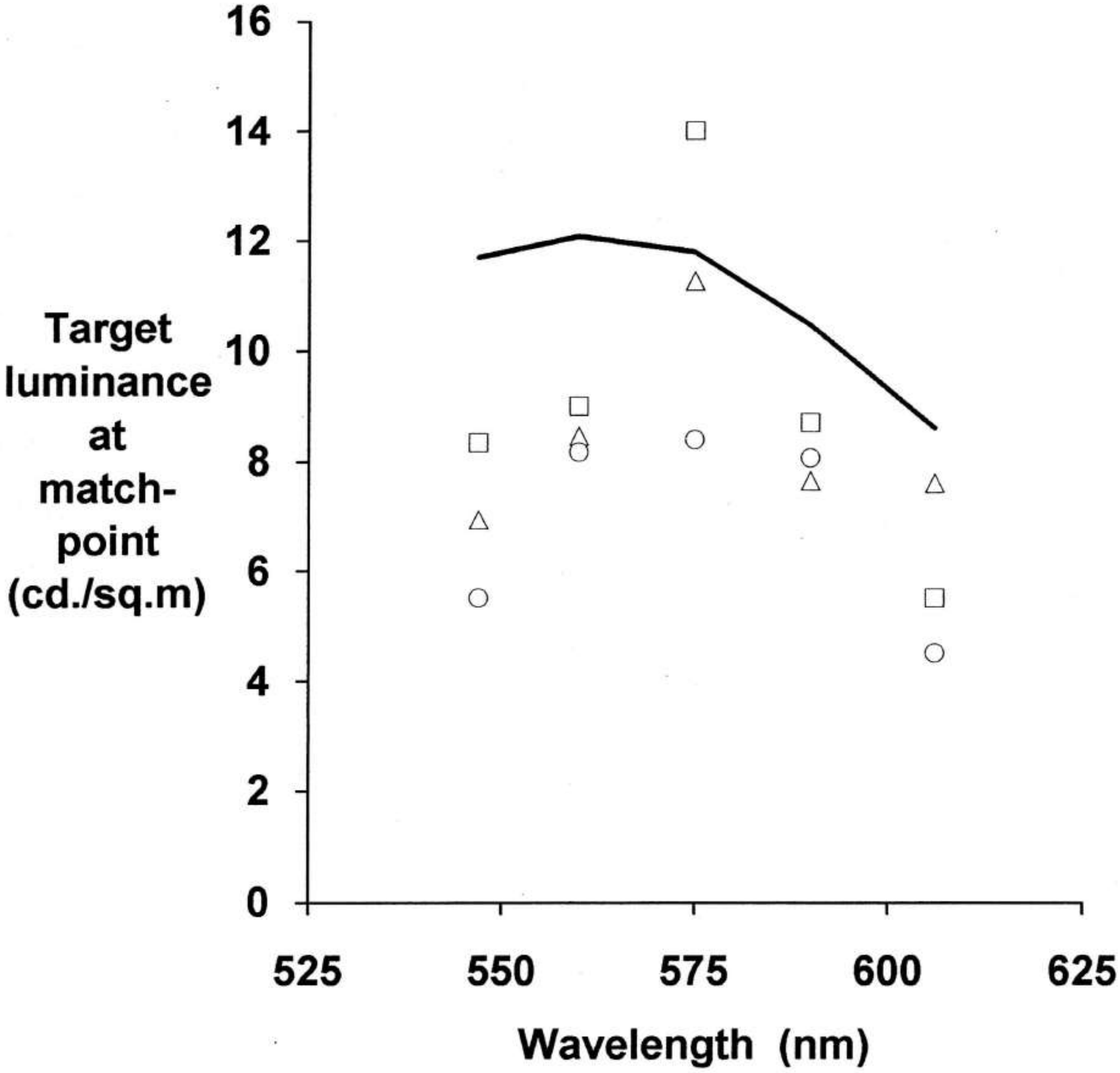

Fig. 4: Heterochromatic colour matching data for the subjects used in this experiment. The solid line is the position predicted by the WARE-COWAN equation; the symbols are for subjects HL (△), JW (□), AR (○).

In so far as such responses represent an involuntary attentional response, our results offer no evidence that this aspect of human behaviour is controlled by brightness rather than luminance.

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