The influence of colour on oculomotor behaviour during image perception

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The aim of this study was to investigate how oculomotor behaviour depends on the availability of colour information in pictorial stimuli. Forty study participants viewed complex images in colour or grey-scale, while their eye movements were recorded. We found two major effects of colour. First, although colour increases the complexity of an image, fixations on colour images were shorter than on their grey-scale versions. This suggests that colour enhances discriminability and thus affects low-level perceptual processing. Second, colour decreases the similarity of spatial fixation patterns between participants. The role of colour on visual attention seems to be more important than previously assumed, in theoretical as well as methodological terms. *NeuroReport* 16:1557–1560 © 2005 Lippincott Williams & Wilkins.

Key words: Colour; Eye movements; Image perception; Oculomotor behaviour; Visual attention

Introduction

The role of colour in attentional control and visuomotor behaviour is still a matter of debate. It has been generally accepted that in typical search tasks, colour is able to elicit 'pop-out', that is, colour is available to preattentive selection [1]. Nevertheless, it has been argued that colour *alone* was not accessible to the neural systems associated with preattentive selection. These systems – especially the superior colliculi – are mainly innervated by the magnocellular stream, whose neurons are believed to be functionally colour-blind [2]. Another hypothesis postulates that colour is processed independently of other sensory attributes, such as form, depth, or motion, and that the role of colour in early image processing is rather limited [3]. Thus, it might seem implausible to assume that colour information is capable of influencing oculomotor behaviour, at least insofar as bottom-up attentional control is concerned. If the role of colour in early image processing was that limited, no difference should occur between viewing grey-scale and colour images, especially in the first 1 or 2 s which are believed to be predominantly under bottom-up control [4,5]. Indeed, early anecdotal evidence suggests that colour or the lack of colour has no appreciable influence on spatial fixation distribution [6,7]. Moreover, a qualitative study on video perception found no differences in scan patterns for the same video clip presented in colour and black-and-white [8]. But meanwhile, there is a growing body of evidence indicating that the role of colour in attentional control – and thus in oculomotor behaviour as well – is not that limited. At least two research groups reported results suggesting that abrupt-onset isoluminant objects can capture attention [9,10], others demonstrated that coloured cues at isoluminance are able to automatically guide attention [11,12]. Thus, the question of whether and how colour influences oculomotor behaviour has not been settled yet. The aim of the present study was to investigate whether such effects of colour can also be demonstrated using complex pictorial stimuli.

Materials and methods

Participants

Forty participants, aged between 24 and 39 years (M=29.8, SD=4.32, 28 women and 12 men), volunteered for the study. They were naïve as to the experimental hypotheses and gave written, informed consent prior to participation. All participants had normal or corrected-to-normal visual acuity, no strabismus, and normal colour vision (Ishihara's Test for Color Deficiency). They were assigned to two groups of equal size (Group A and B), which were age and sex-matched. No financial or other reward had been offered. The study was approved by the local ethics committee.

Stimuli

Three sets of 12 colour images each were selected. The first set contained photographic pictures of natural scenes. For the second set, image material from the works of 20th century artists (W. Kandinsky, P. Klee, F. Marc, J. Pollock, and P. Mondrian) was chosen. The third set consisted of computer-generated fractals. For examples of the stimuli, see Fig. 1.

Each image was converted into a grey-scale version, by converting the red–green–blue (RGB) values to National Television System Committee (NTSC) coordinates, setting

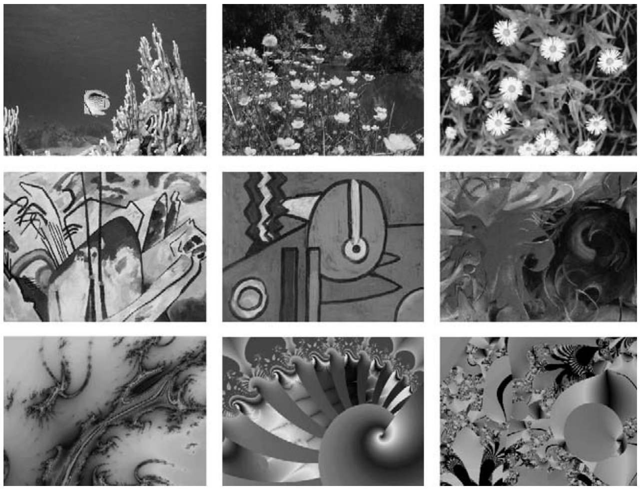

Fig. 1. Stimulus examples.

the hue and saturation components to zero, and converting back to RGB colour space. This algorithm is widely used in common image processing applications.

Apparatus

The images were presented in a dimly lit room on a 19″ cathode ray tube display (Philips Brilliance 109MP, Philips Electronics, Eidenhoven, The Netherlands) with a resolution of 800×600, 24-bit colour depth, and a vertical refresh rate of 85 Hz (noninterlaced). The active screen size was $29^\circ \times 22^\circ$ of viewing angle. Eye position was recorded with an infrared video-based tracking system (EyeLink, SensoMotoric Instruments GmbH, Teltow, Germany), which has a temporal resolution of 250 Hz, a spatial resolution of 0.01° and a gaze-position accuracy relative to the stimulus position of 0.5°–1° (manufacturer's specifications). As the system incorporates a head movement compensation, a chin rest was sufficient to reduce head movements and ensure constant viewing distance.

Procedure

Every image presentation was preceded by a central fixation point (a black dot of 0.5° diameter on a light grey background) for 1.5 s, enforcing the same starting point for all participants and allowing for periodical recalibration. The images were presented for 5 s each. In order to provide participants with a well defined task, they were instructed to view the images in preparation for a recognition test to be carried out after the last image of each block. Each image was shown to a participant in one version only; one half of all images in grey-scale, the other half in colour version to Group A, and vice versa for Group B. The sequence of image versions and types was varied from block to block; block and image sequence was identical for all participants.

Data analysis

Mean fixation duration and saccade amplitude were calculated for three consecutive time intervals (T1, T2, and T3) of 1.5 s each, so as to be able to detect changes in the temporal domain.

In order to analyse the influence of colour on the inter-participant similarity of fixation patterns on a given image, we used an adaptation of the index of similarity measure [4]. This measure characterizes the similarity of fixated locations between different participants, irrespective of the temporal sequence of fixations. The similarity index I_s, designed to specify the similarity between two sets of locations $P_i(x, y)$ and $P_j(x, y)$ in a two-dimensional image, is defined as

$$I_s = \left(1 - \frac{D}{D_r}\right)100, \tag{1}$$

where

$$D^2 = \frac{n_1 \sum_{j=1}^{n_2} d_{2j}^2 + n_2 \sum_{i=1}^{n_1} d_{1i}^2}{2n_1 n_2 (a^2 + b^2)}, \tag{2}$$

where n_1 and n_2 are the number of locations in the two sets, d represents the distances between a fixation in one set and its nearest neighbour in the other set, and a and b are the image dimensions. D is the calculation for the two empirical fixation distributions under scrutiny, whereas D_r stands for the value for random sets of locations with the same number of fixations as in the empirical data, serving as the baseline. For our study, we adapted the index to specify the similarity *between* participants. To this end, the fixated locations were compared, separately for each image and image version, by calculating I_s for all pairs of traces made by two participants in response to the same image, and averaging these values over all possible pair comparisons. Again, these computations were performed for the three temporal intervals described above. Furthermore, we calculated baseline values expressing the overall similarity of traces I_o (see [4] for further details).

Statistical hypothesis testing was performed by using repeated general linear model (GLM) statistics (SPSS 11.0.0, SPSS Inc., Chicago, Illinois, USA). If necessary, deviations from the sphericity assumption were compensated for by correcting the degrees of freedom (method of Huynh-Feldt). For post-hoc testing, multiple pairwise comparisons were applied.

Results

Mean fixation duration on colour images was significantly shorter than that on grey-scale images [$F(1,39)=8.862$, $P<0.01$]. A significant effect of time was also found [$F(1.637,63.83)=22.33$, $P<0.001$]. Post-hoc testing indicated the mean duration of fixations in time interval T2 to be about 13 ms longer than in interval T1 ($P<0.001$) and a further increase of 6 ms from interval T2 to T3 ($P<0.05$). No significant image version $\times$ time interval interaction was found [$F(2,78)=0.008$], demonstrating that the effect of colour is already apparent during the first few fixations (Fig. 2, left panel).

No significant effects of colour on saccade amplitude (Fig. 2, middle panel) were found [$F(1,39)=2.815$, $P=0.101$]. Saccade amplitude, however, was significantly affected by time [$F(1.760,68.62)=7.1$, $P<0.01$], with a decrease from T2 to T3 ($P<0.001$). No significant interaction was found between the two factors [$F(2,72.76)=1.324$, $P=0.272$].

Regarding the analysis of spatial fixation patterns, we found that on colour images, the similarity index was significantly lower than on the grey-scale images [$F(1,35)=5.334$, $P<0.05$]. In other words, the viewing behaviour of different participants was more similar when

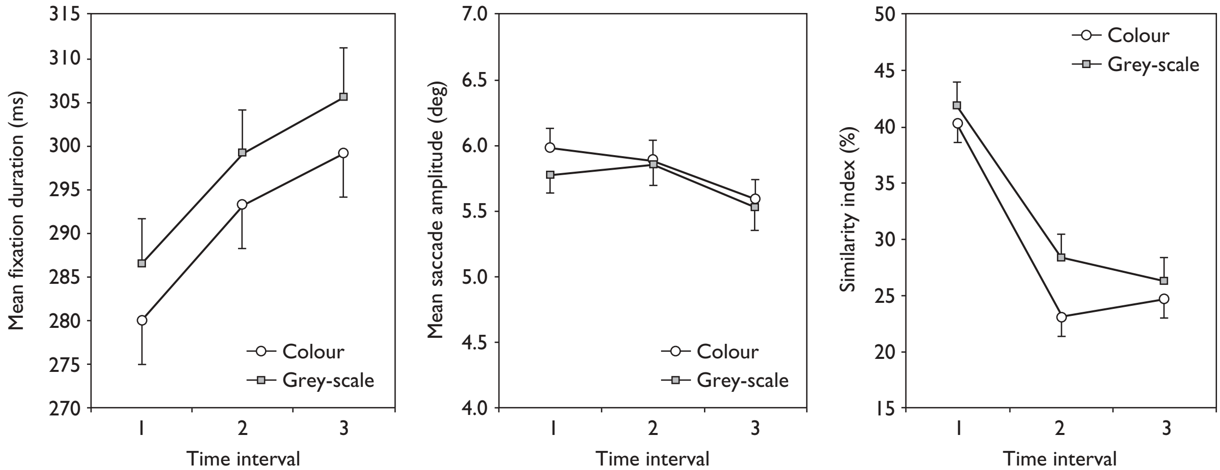

Fig. 2. Temporal course for three time windows of 1.5 s each. Left panel: mean fixation duration. Middle panel: mean saccade amplitude. Right panel: interparticipant similarity index. Error bars show the standard error of the mean.

images were presented in grey-scale. An effect of time was observed as well [F(2,70)=104.3, $P<0.001$], with a significant decrease in similarity from interval T1 to T2 ($P<0.001$), while the values in intervals T2 and T3 did not differ from each other (F<1). In this analysis, no significant interaction of image version and time interval was found [F(1.748,61.17)=1.358, $P=0.263$].

The baseline values were calculated for the entire viewing time, resulting in $I_{o,Colour}=12.52$ and $I_{o,Grey\text{-}scale}=16.07$. Both values are significantly lower than the corresponding I_s values [colour: $t(35)=37.19$, $P<0.001$; grey-scale: $t(35)=37.3$, $P<0.001$; two-tailed paired sample *t*-tests], underlining that I_s indeed expresses a similarity within an image which goes beyond a general similarity based on effects such as a commonly observed central tendency or similar image layouts.

Discussion

The first main finding of our study is that fixation duration while viewing colour images was significantly shorter than while viewing their grey-scale equivalents. This difference was apparent during the whole viewing time, including the first few fixations. This might seem unexpected, as the conversion from colour to grey-scale actually reduces the complexity of an image, which is believed to decrease fixation duration. In our case, however, shorter fixations on colour images indicate that it might be easier for the visual system to extract the information from colour images than from grey-scale ones. It has been suggested that colour helps the visual system to segment complex images into separate, identifiable objects, resulting in a coding advantage for coloured over grey-scale images [13]. As it seems plausible to argue that the duration of a fixation is determined by the amount of time required to perform the intended feature encoding [14], we assume that the presence or absence of colour affects the ease of information extraction, or *discriminability*. It is also worth noting that a significant difference in fixation duration was already apparent during the first 1.5 s of viewing. This underlines that the effect of colour on fixation duration is caused by basic, bottom-up mechanisms such as information extraction, which is dependent on discriminability. Top-down mechanisms (strategy, schemas, etc.) would be expected to exert their influence only later during a trial [4].

The second main finding was that on grey-scale images, different participants placed their fixations in a more similar fashion than on the colour images, i.e. a higher similarity index value was found for grey-scale images. This is in accordance with a current approach to visual attention, the *saliency map approach* [15,16]. The basic assumption of this model is that the selection of foveation targets is based on a few feature channels (e.g. luminance, contrast, colour, and orientation). These channels are separately evaluated in a centre-surround manner, and their outputs are combined into the final saliency map on the basis of which fixation locations are programmed. In consequence, cancelling information fed into any of these channels – the colour channel in our experiment – reduces the number of potential fixation targets. As targets predominantly defined by colour are absent in grey-scale images, less potentially meaningful (i.e. perceptually salient) fixation targets are available. In consequence, the similarity of fixation patterns between individuals increases.

Our results suggest that the role of colour in visual attention is more important than previously assumed. They are in line with several recent findings from associated fields. First, a computer-vision algorithm based on the above-mentioned *saliency map approach* has been compared with human behaviour. When chromatic information was included in the calculations, the algorithm proved to be more successful than when this information was disregarded [5,17,18]. Second, at least for some aspects of visual stimuli, colour information seems to be available for preattentive selection: purely chromatically defined targets of different orientation can be detected pre-attentively (i.e. pop-out was achieved under isoluminance conditions [19]) and the abrupt onset of colour-defined objects can even capture attention when they are isoluminant [9,10]. Third, preattentional effects of coloured cues at isoluminance are able to automatically guide attention [11,12]. And finally, recent theories of colour vision in primates underline the general importance of colour information (e.g. [20]).

Conclusion

The results presented in this paper demonstrate that colour information has a large influence on the control of visual behaviour, and that this influence can be observed during viewing of complex visual stimuli. Although the complexity of an image increases with the inclusion of colour information, fixation durations are not increasing, but decreasing. This is attributed to a colour-associated enhancement of stimulus discriminability. Moreover, colour effectively decreases inter-participant similarity of the spatial fixation patterns, because with colour, there are more promising targets for visual inspection than without. This corroborates current theories of preattentive selection on the basis of saliency maps. As a whole, our findings also have methodological implications. From the viewpoint of ecological validity, it seems questionable to use grey-scale stimuli in general scene viewing experiments, unless the use of achromatic stimuli is indicated for theoretical reasons.

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