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# Neural computation of perceived relative size and depth in complex 2D image configurations

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**Abstract**—The ability of the human perceptual system to extract 3D information on the basis of 2D cues in planar images is important to the development of effective interface technology. The functional principles of this perceptual ability of humans are still not fully understood. It is known that differences in local luminance contrast and physical size of critical parts of 2D images may generate monocular cues to 3D, however, subjective 3D cues are also available in 2D images without physical differences in either luminance or size of critical local parts. The results of this study here show interactions between local color, brightness contrast, and general background intensity of complex configurations generating significantly correlated differences in perceived size and depth of local image parts. The fundamental relevance of the findings is linked to the technological development of image-guidance systems for human action.

*Keywords* - colour; local contrast; background intensity; complex images; 2D image parts; subjective size; relative depth.

## I. INTRODUCTION

Differences in local luminance contrast in planar images have been mentioned to generate powerful 2D cues to perceived 3D depth since Leonardo da Vinci [1]. Neural models and psychophysical data predict that contrast variations across image parts, indeed, directly determine which parts in the image will be seen as "nearer" or "further away from" the human observer [1-10]. Previous studies of functional links between local image contrast and the perception of 3D properties have not yet fully explored all the, potentially powerful and important, interactions between color, luminance, and general background field intensity. Certain colors in combination with specific contrast intensities produce a more powerful perception of 3D effects than others, for example [10, 1-14]. Variations in brightness or luminance displayed across two or more different surface layers in complex 2D multiple-surface configurations may alter these perceptual effects significantly [7, 14, 15], or even reverse them [17]. This study here was designed to explore some of such possible interactions systematically. Complex configurations with carefully controlled physical variations in local color, luminance, and general background intensity were generated for this purpose. The local physical size of test and reference surfaces submitted to perceptual judgments was not varied. The image configurations were displayed on a high resolution monitor in a computer

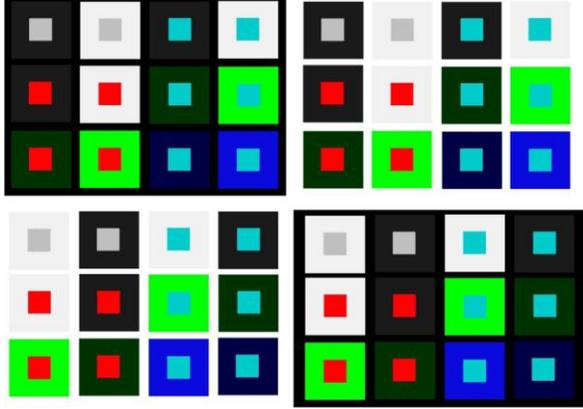
controlled study with four two-alternative forced choice psychophysical judgment tasks. Human observers had to judge which of two comparison surfaces in the configurations appeared "bigger" (task 1) or "nearer" (task 3), and which of all the possible reference surfaces in a given configuration appeared "the biggest" (task 3) or "the nearest" (task 4) of all.

## II. MATERIALS AND METHODS

Image configurations were computer generated and displayed on a high resolution color monitor (EIZO COLOR EDGE CG 275W, 2560x1440 pixel resolution) connected to a DELL computer equipped with a high performance graphics card (NVIDIA). Color and luminance calibration of the RGB channels of the monitor was performed using the appropriate Color Navigator self-calibration software, which was delivered with the screen and runs under Windows 7. RGB values here correspond to ADOBE RGB. All luminance levels were cross-checked with an external photometer (OPTICAL, Cambridge Research Systems). RGB coordinates, luminance parameters (cd/m<sup>2</sup>), and color coordinates (X, Y, Z) of the different reference surfaces in the image configurations from this study are given in Table 1.

The size of each of the square surfaces in the center of each of the twelve local configurations in the images was 160x160 pixels, the size of each of the square surrounds was 400x400 pixels. The twelve local configurations were equally spaced, with 50 pixels between their surrounds, along the horizontal and vertical dimensions. They were displayed centrally on the dark and light general background of the 2560x1440 pixel screen. The size of a single pixel on the screen is 0.023 cm.

Grey, red, and blue-green center squares on their light and dark immediate surrounds were presented in pairs, as shown in Figure 1. Their position (left, right) in a pair was counterbalanced between trials and subjects. Presentation on light and dark general backgrounds was also counterbalanced between trials and subjects. Ten subjects, comfortably seated in a semi-dark room, in front of the EIZO monitor at a viewing distance of about 1 meter, had to perform four psychophysical judgment tasks.



**Figure 1.** Center-surround surface configurations on dark and light general backgrounds. The twelve local configurations produce subjective differences in the relative size and depth of the centrally displayed squares. Grey, red, and blue-green center squares displayed on dark and light surrounds were paired for the relative psychophysical judgments.

In the first task, they had to decide which of the two central squares in a paired configuration (*paired comparison*) appeared to be the "bigger" one of the two. In the second task they had to pick the central square from all of the twelve configurations that appeared the "biggest" of all (*single pick*). In the third task, they had to judge which of the two central squares in a paired configuration (*paired comparison*) appeared to be "nearer" to them, and in the fourth task they had to pick the central square from all of the twelve configurations that appeared the "nearest" of all (*single pick*) to the observer.

TABLE I.

Reference Surface	Image Luminance ( $L$ ) And Color Coordinates						
	$R$	$G$	$B$	$L$ ( $cd/m^2$ )	$X$	$Y$	$Z$
Grey Center	190	190	190	58.6	49.8	52.3	57.0
Red Center	255	0	0	35.8	57.7	29.7	2.7
Blue Center	0	205	205	52.3	23.1	43.5	65.7
Dark-Grey Surround	25	25	25	2.0	0.6	0.6	0.6
Light-Grey Surround	240	240	240	95.3	83.2	87.5	95.3
Dark-Green Surround	0	50	0	2	0.5	1.7	0.2
Light-Green Surround	0	255	0	78.5	18.5	62.7	7.1
Dark-Blue Surround	0	0	70	0.5	1.1	0.4	5.8
Light-Blue Surround	10	10	220	5	13.7	5.52	71.6
Dark General Background	0	0	0	0.5	0	0	0
Light General Background	255	255	255	120.0	13.7	5.52	71.6

Trials were sequenced in counterbalanced sessions producing eight psychophysical judgments for each *paired comparison* and *single pick task*, general background

condition, and subject. Therefore, a total of 80 data was generated for each of the four tasks and for each of the two general background conditions

The subjects who participated in this study were ten adult volunteers, seven men and three women, with normal vision. The experiments were conducted in accordance with the Declaration of Helsinki (1964) and with full approval of the corresponding author's host institution's (CNRS) ethical standards committee. Informed consent was obtained from each of the participants.

### III. RESULTS AND DISCUSSION

#### A. Response probabilities for "bigger" and "nearer"

The response probabilities ( $p$ ) from the two paired comparison tasks (task 1, task 3) were calculated for each of the twelve local center-surround configurations in the order in which they are displayed in the first of the four general display-panels shown in Figure 1. A  $p$  of 1 would correspond to the case where a local configuration of a given pair produces a total number of 80 observed/80 possible responses for "bigger" or for "nearer". In this case, the  $p$  associated with the other configuration from that pair would be 0. In the case a given pair produces random perceptual responses for "bigger" or for "nearer", the response probability associated with each of the two paired configurations would be 0.50. In a first analysis, the twelve configurations were sorted as a function of the magnitude of the response probabilities they produced for "bigger" and "nearer" and plotted in ascending order (Fig 2a) for each of the two "general background intensity" conditions. These two graphs reveal consistent  $p$  distributions for "bigger" and "nearer" ranging from 0.10 to 0.90 in each of the two general background conditions.

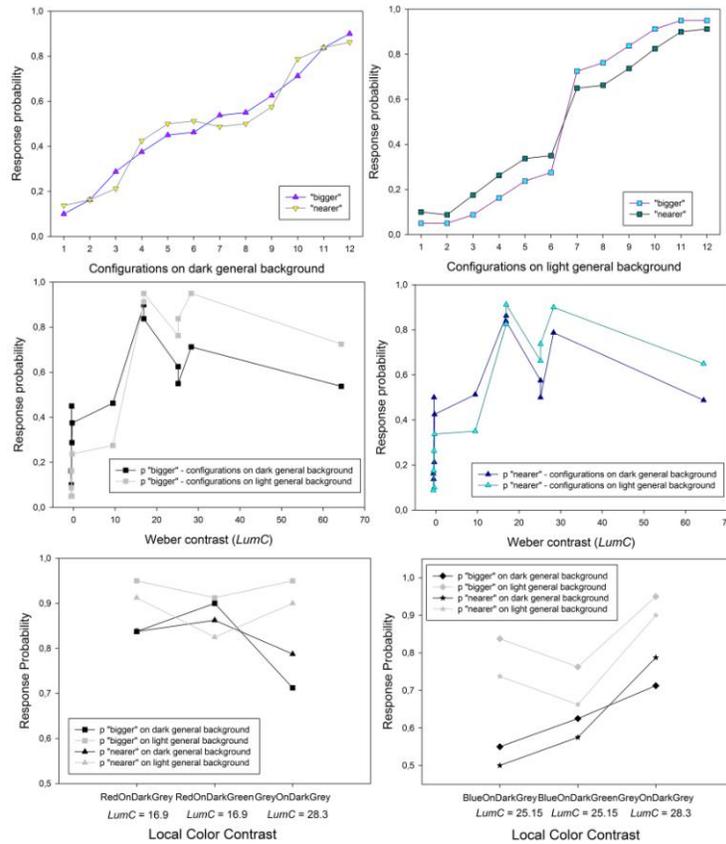
#### B. Correlation between response probability distributions from the paired comparison tasks

The response probability distributions from the paired comparison tasks were submitted to statistical correlation analyses (Pearson's product moment), returning statistically significant correlation coefficients ( $P$ ), with 0.98 ( $p < .001$ ) for "bigger" and "nearer" in the "dark general background" condition, and 0.99 ( $p < .001$ ) for the probability distributions for "bigger" and "nearer" in the "light general background" condition. These analyses show that the center-surround configurations produced a wide range of significantly correlated perceptual differences in relative size and depth of their local center surfaces.

#### C. Response probabilities for "bigger" and "nearer" as a function of luminance contrast

In a second analysis, the configurations were sorted as a function of their local contrast intensity. The luminance contrasts (Weber ratios) of the twelve local center-surround configurations were calculated using

$$L_{center} - L_{surround} / L_{surround}. \quad (1).$$



**Figure 2.** Response probability ( $p$ ) distributions for relative size ("bigger of two") and relative depth ("nearer of two") judgments from the *paired comparison* tasks (a) the top panel shows significantly correlated magnitudes of  $p$  for "bigger" and "nearer" produced by the twelve configurations on the two general backgrounds, plotted in ascending order (b) the middle panel shows  $p$  distributions as a function of the luminance contrast intensity (Weber ratios) of the twelve configurations and the general background condition (c) the bottom panel shows  $p$  as a function of the local color contrast of the configurations with positive (+) Weber contrasts, which produced the greater magnitudes of  $p$  for "bigger" and "nearer" in the paired comparison tasks.

The response probabilities for "bigger" and "nearer" were then plotted as a function of the twelve different Weber contrasts of the configurations and the two general background conditions (Fig 2b). These graphs reveal that there is no simple function linking the  $p$  for relative size and depth to the luminance contrast of the local configurations. There is a systematic effect of the general background condition on all the  $p$ : the lighter general background produced systematically stronger response probabilities for "bigger" and "nearer". The configurations with the positive local contrast signs all produced greater magnitudes of  $p$  in comparison with their negative-contrast-sign pairs, however, the configurations with the strongest positive contrasts did not produce the highest response probabilities, neither for "bigger" (relative size), nor for "nearer" (relative depth) in the paired comparison tasks. This is clarified further by the graphs shown in the panel at the bottom (Fig 2c), where  $p$  for "bigger" and "nearer" are shown as a function of the local color contrast of the configurations which produced the stronger  $p$  magnitudes, and as a function of the general background condition. The highest  $p$  for "bigger" (relative size) and "nearer" (relative depth) are produced by the RED central squares on the dark-grey surround displayed on the

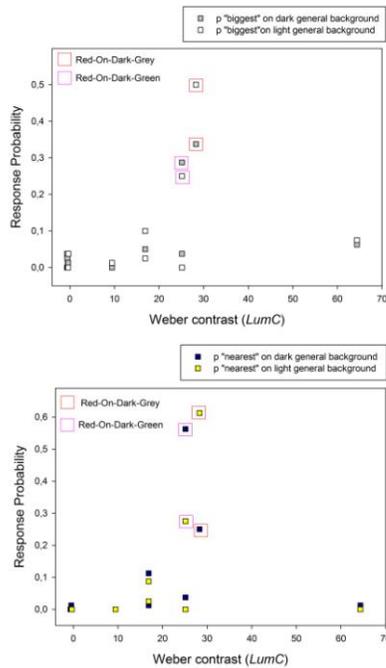
light general background, and by the GREY central squares on the dark grey surrounds displayed on the general background. The BLUE central squares on dark surrounds produced noticeably lower  $p$  for "bigger" and "nearer" in comparison with the RED centers, yet, the blue on dark surrounds has a much stronger luminance contrast (25.5) than the red on dark surrounds (16.9). For the blue centers on dark surrounds we observe the strongest effect of general display background condition: the  $p$  for "bigger" and "nearer" are well above a certain positive probability threshold ( $\geq 0.75$ ) for the blue-on-dark configurations displayed on a light general background, but approach the chance level ( $\sim 0.50$ ) in the condition where they were displayed on the dark general background.

#### *D. Response probabilities for "biggest of all" and "nearest of all" as a function of luminance contrast*

In the final analysis, we plotted the  $p$  distributions from the two *single pick* tasks as a function of the contrast intensity of the twelve local configurations and the general display background condition (Fig 3). These results consistently show that the highest  $p$  for "biggest" and "nearest" are produced by RED on dark local surrounds.

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**Figure 3.** Response probability distributions for "biggest of all" and "nearest of all" as a function of local Weber contrasts and general background condition from the two *single pick* tasks.

## IV. CONCLUSIONS

The results highlight complex interactions between color, local luminance contrast and global display background in the production of perceptual effects of subjective relative size and depth. Some of them, but not all, are predicted by neural theories [14,17]. Perceived size and depth are significantly correlated, therefore, subjective differences in size generate 2D cues to 3D properties functionally equivalent to "real", physically grounded, monocular depth cues. This supports existing computational models of relative surface depth from ambiguous contrast input [7,14,16], producing functional perceptual responses for effectively guiding selective attention in motor tasks [10,17,18]. Lighter general backgrounds systematically produce stronger effects, irrespective of the local color or contrast of image parts. This has potentially important implications for the development of interface technology for image-guided systems designed to assist human operators in precision tasks. Finally, the results here confirm, once again that the color red is the most likely to produce the strongest depth effects, with a clear competitive advantage over other colors such as green [9] or blue [11] in the likelihood to be perceived as closer to the human observer.

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