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ABRUPT LUMINANCE CHANGE POPS-OUT; ABRUPT COLOR CHANGE DOES NOT

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SUMMARY

The present study investigated whether an isoluminant color change pops-out indicating that it can be detected pre-attentively in parallel. Experiment 1 shows that an abrupt color change presented on an isoluminant background does not pop-out. However, when the color change is accompanied by a small luminance change, it pops-out and attracts attention. Experiment 2 shows that the pop-out is fully due to the luminance change and not to the color change. Experiment 3 shows that the failure to find a pop-out at isoluminance cannot be attributed to the limited temporal resolution for chromatic stimuli. The results are in agreement with physiological findings regarding the parvo and magno system.

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Abrupte luminantieveranderingen geven een pop-out; abrupte kleurveranderingen niet

J. Theeuwes

SAMENVATTING

In deze studie werd gekeken of een isoluminante kleurverandering aanleiding kan geven voor een "pop-out" wat impliceert dat zo'n verandering pre-attentief en parallel gedetecteerd zou kunnen worden. Experiment 1 laat zien dat een abrupte kleurverandering gepresenteerd tegen een isoluminante achtergrond geen pop-out geeft. Wanneer de kleurverandering samen gaat met een (kleine) luminantieverandering treedt er wel een pop-out op. Experiment 2 laat zien dat deze pop-out volledig veroorzaakt wordt door de luminantieverandering en niet door de kleurverandering. Experiment 3 laat zien dat het afwezig zijn van een pop-out bij isoluminantie niet toegeschreven kan worden aan de beperkte temporele resolutie van het kleursysteem. De resultaten zijn in overeenstemming met fysiologische bevindingen aangaande het parvo en het magno systeem.

1 INTRODUCTION

If a single red object is embedded in an array of green objects, it is seen immediately without effort; a phenomenon known as visual "pop-out" (Treisman & Gelade, 1980). One can speak of a "pop-out" when the time to detect the object is hardly affected by the number of elements in the display (less than 5- or 6- ms per element; Treisman & Souther, 1985). The object with a unique feature is detected through early, spatially parallel and automatic encoding, and its presence tends to call attention itself (Treisman & Gormican, 1988). The calling of attention is the basis for the pop-out phenomenon (Treisman, 1988), and suggests that a popping-out element attracts attention to its location. This type of parallel pre-attentive processing is contrasted with attentive processing in which serial scanning through the display is necessary in order to detect the target. In the latter type of tasks, the time to find the object linearly increases with the number of elements in the display. The early perceptual pre-attentive encoding causing an object to pop-out from its background, is limited to a particular set of primitive features, such as orientation of edges, color, brightness, and shape.

Recent evidence shows that abrupt luminance onsets (e.g., Yantis & Jonides, 1984; Müller & Rabbitt, 1989; Theeuwes, 1991, 1993), abrupt luminance offsets (Theeuwes, 1991) and abrupt luminance changes (Theeuwes, 1990) do pop-out in an array of stationary elements that do not have a luminance change. It has been shown that abrupt onsets and offsets can capture attention in a stimulus-driven fashion (e.g, Theeuwes, 1991, 1993; Yantis & Jonides, 1984, 1990).

It has been suggested that an abrupt visual event captures attention by triggering the *transient* channels in the primate visual system (e.g., Breitmeyer & Ganz, 1976; Todd & Van Gelder, 1979; Yantis & Jonides, 1984). Y-cells or magno-cells are at the basis of the transient channel, and these cells with their corresponding retina-brain pathways are particularly involved in luminance processing and respond selectively to abrupt changes in visual stimulation such as onsets, offsets and movement (e.g., Livingstone & Hubel, 1988; Zeki & Shipp, 1988). The magno-system is basically color-blind and responds fast to temporal changes in luminance. X-cells or parvo-cells are at the basis of what is called the *sustained* channel. This channel is relatively slow and is particularly involved in processing detailed patterns and color information.

This physiological evidence is corroborated by psychophysical experiments on movement perception. For example, Cavanagh, Tyler and Favreau (1984) showed that the perceived velocity of moving red and green isoluminant sinewave bars was substantially slowed. The grating often appeared to be static. Subjects only appreciated some motion because they occasionally noticed that the bars had changed position. Recently, Lüschow and Nothdurft (1992) showed that subjects could not detect pre-attentively a single moving line in a stationary texture when present on an isoluminant background.

The present study investigated the characteristics of the transient-sustained (magno-parvo) system in visual search. More specifically, it was tested whether abrupt color change at isoluminance can capture attention when subjects are set to look for it. Subjects viewed a multi-element display consisting of 4, 9 or 19 elements. After 50 ms (Exp. 1 and 2) or 100 ms (Exp. 3) an identical element was added to the display. Subjects were required to detect this added element. All elements, including the added element, had either the same luminance as the background (isoluminant) or had either a higher or lower luminance than the background.

If subjects are capable of responding to any abrupt temporal change occurring in the visual field then one might expect that abrupt color change can capture attention. Alternatively, if a change in luminance is necessary to allow capture of attention then it is expected that no pop-out occurs at isoluminance. Under the same conditions, a pop-out is expected when an abrupt luminance change is introduced.

The main interest of the present study was whether an abrupt *change* (luminance or color) does pop-out and can be detected in parallel. In other words, when the target pops-out, it must be ensured that the pop-out is due to the detection of the change and not to any other confounding factor. First, there might be confounding effects of memory. For example, it is possible that an object pops-out because subjects notice that an element that previously was not present within the display, has been added. In that case subjects did not detect the actual change, but they can infer the change by comparing the two displays (as for example in Cavanagh et al., 1984). Second, it is possible that a colored element pops-out because of local chromatic adaptation (Theeuwes & Lucassen, 1993). For example, when subjects are looking at a display containing green elements against a gray background, subjects get adapted to the gray and green color. If one adds a new green colored isoluminant element to such a display, the newly added green element will pop-out not because subjects detected the change but because chromatic adaptation causes the newly added green element to have a color which is slightly different from the other green elements. Theeuwes and Lucassen (1993) showed that chromatic adaptation to a display presented longer than 100 ms can cause an element to pop-out from an array of other apparently identical elements.

In order to ensure that these confounding effects could not play a role, large display sizes were used so that it is impossible to memorize and compare the sequentially presented pattern of elements. In addition, the target circle was added either 50 ms (Experiment 1 and 2) or 100 ms (Experiment 3) after display onset, times too short for a (strong) chromatic adaptation to build up (e.g., Theeuwes & Lucassen, 1993).

2 METHOD

2.1 Experiment 1: Green elements on a gray background

Subjects

Two experienced observers (a graduate student and the author) participated in all experiments. Both had normal or corrected-to-normal visual acuity and reported having no color defects.

Apparatus and Stimuli

A NEC Multisync 3D VGA color CRT (resolution 640×350) controlled by SX-386 Personal Computer (G2) was used for presenting the stimuli. The computer controlled the timing of the events, generated pictures and recorded reaction times. The "/"-key and the "z"-key of the computer keyboard were used as response buttons. Each subject was tested in a sound-attenuated, dimly-lit room, his head resting on a chinrest. The CRT was located at eye level, 103 cm from the chinrest.

The display consisted of green outline circles (CIE x,y chromaticity coordinates of .306/.588) presented on a gray background (x,y = .259/.277). The central fixation cross and line segments located within the outline circles of the search display were presented in red (x,y = .259/.277). The gray, red and green colors were matched for luminance by means of a flicker fusion test (Ives, 1912). In this test, two color patches were presented at the same location in fast successive order (60 Hz). Subjects adjusted the brightness of one patch until the luminance flicker was at a minimum.

Procedure

The task was similar to that in Theeuwes (1991, 1992; Theeuwes & Lucassen, 1993), consisting of a visual search task in which there is a clear distinction between the defining and reported attribute of the target. Subjects responded to the orientation (horizontal or vertical) of the red line segment appearing in one of the circles of the search display. Because a horizontal or vertical target line segment does not pop-out in a field of slightly tilted line segments, it was ensured that detecting the line segment required local focussed attention (Theeuwes, 1991; Treisman & Gormican, 1988). Throughout a trial a fixation cross was presented at the center of the display. The search display consisted of 5, 10 or 20 green outline circles (1.22° outside diameter and 1.10° inside diameter) which were presented randomly at any of 30 locations in a 6 by 5 rectangular stimulus array (10.1° × 7.0°). Separation of nearest contours between the circles was .80° in the X-direction, and .55° in the Y-direction.

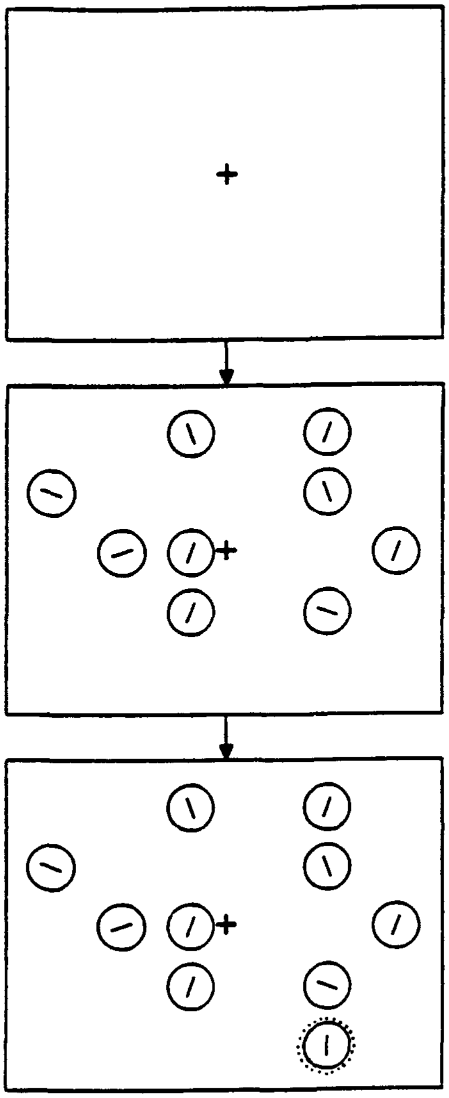

Fig. 1 Example of trial events display size 10. Initially 9 circles are presented randomly at any of the 30 locations in a 6 × 5 rectangular stimulus array. After 50 ms, an identical circle containing the response requiring line segment is presented at any of the remaining empty locations. In this particular example at the bottom of the display.

At the beginning of a trial, the fixation dot at the center of the monitor was presented for 2000 ms. Along with the fixation dot, a display was presented consisting of 4, 9 or 19 green outline circles, each containing a red line segment (.55°) that was tilted 20° to either side of the horizontal or vertical plane. The orientations were randomly distributed in a display. After 50 ms, an additional green outline target circle containing either a horizontal or vertical line segment, was presented at one of the remaining empty locations of the 5 × 6 array. The line segment located in this added target circle determined the appropriate response key (the "/"-key for vertical and the "z"-key for horizontal). The location of the added target circle containing the target line segment was randomized from trial to trial. Also, display size (5, 10, 20) was randomized within blocks from trial to trial. The search display remained present until a response was emitted. If no response was made after 4 s, the trial was counted as an error. Figure 1 provides an example of the trial events.

The luminance of the added green outline circle was systematically varied between values above and below the luminance of the background. For each subject, the luminance value of green at isoluminance obtained by the flicker criterion was used as a starting point and the smallest possible steps in luminance change around the isoluminance criterion were determined. This resulted in 4 luminance steps below and 4 luminance steps above the background luminance. In addition, two baseline conditions were included: in one condition the green outline circle was presented at about half of the background luminance, in the other at about twice the background luminance. In total, this resulted in 11 luminance conditions. Each luminance condition was run in a separate block of 90 trials, in which there were equal number of trials at each display size level (5, 10, 20) and equal number of trials with a horizontal or vertical line segment. The order of presentation of the blocks was random.

The outline circle to background luminance ratio ($L_{circle}/L_{background}$) was used as a contrast measure. Before each block of 90 trials, the luminance of the green circles was changed and its colorimetric and photometric characteristics were measured by means of a spectro-radiometer (Photo Research, type: PR 703 A/M). Only the luminance of the green circle was changed but not its chromaticity coordinates. The luminance of the red line segment inside the green circle was constant during the whole experiment.

Within each block of trials, there were short breaks after 45 trials in which subjects received feedback about their performance (percentage errors and mean reaction time) on the preceding block of trials. Subjects were aware that the outline circle that was added 50 ms later contained the response requiring line segment. They were instructed to look for the added circle. Both speed and accuracy were emphasized. A warning beep informed the subject that an error had been committed.

2.2 Experiment 2: Gray elements on a gray background

Experiment 2 was identical to Experiment 1, except that the outline circles were now gray. The line segments in the outline circles were red isoluminant with the background (all colors had the same CIE values as in Experiment 1). Note that at isoluminance, the outline circles were identical to the background, so that the stimulus field only consisted of isoluminant red line segments. Subject JT performed 9 luminance conditions, subject NK performed 10 luminance conditions.

2.3 Experiment 3: Green elements on a gray background with a 100 ms ISI

Experiment 3 was identical to Experiment 1, except that the interstimulus interval (ISI) between the stimulus field and the target circle was 100 ms instead of 50 ms. Both subjects performed 10 luminance conditions in a random order.

3 RESULTS AND DISCUSSION

3.1 Experiment 1

The best fitting linear search functions defined as reaction time as a function of number of elements in the display was calculated for each subject, at each luminance contrast ratio. Table I gives the search slopes, intercepts and the error rates.

Table I Experiment 1: Slopes, intercepts and error scores for the various contrast ratios ($L_{circle}/L_{background}$).

luminance contrast subject JT	intercept [ms]	slope [ms/ element]	error score [%]	luminance contrast subject NK	intercept [ms]	slope [ms/ element]	error score [%]
0.46	465	-0.11	9.0	0.45	583	-1.46	6.4
0.81	529	-0.57	7.7	0.68	709	-0.22	6.4
0.86	576	1.21	6.4	0.81	597	7.39	6.4
0.92	656	11.37	7.7	0.87	576	18.29	7.7
0.99	564	51.74	5.1	0.92	528	41.69	7.7
1.06	471	72.86	15.4	1	529	49.00	7.7
1.13	804	30.90	2.6	1.07	586	64.72	9.0
1.20	526	28.77	5.1	1.13	631	29.08	9.0
1.27	575	3.68	7.7	1.18	625	31.06	6.4
1.38	518	-0.56	10.2	1.37	683	8.51	9.0
1.98	448	-0.26	7.7	1.83	621	0.47	7.7

Figure 2 presents these slopes as a function of luminance contrast ratio ($L_{circle}/L_{background}$). The dotted lines in Figure 2 indicate the 6 ms/element slope. Search functions with slopes less than 6 ms/element are considered to be characteristic of search processes for elements that pop-out. As is clear from Fig. 2, at near isoluminance the target element does not pop-out and serial search is required to detect the target.

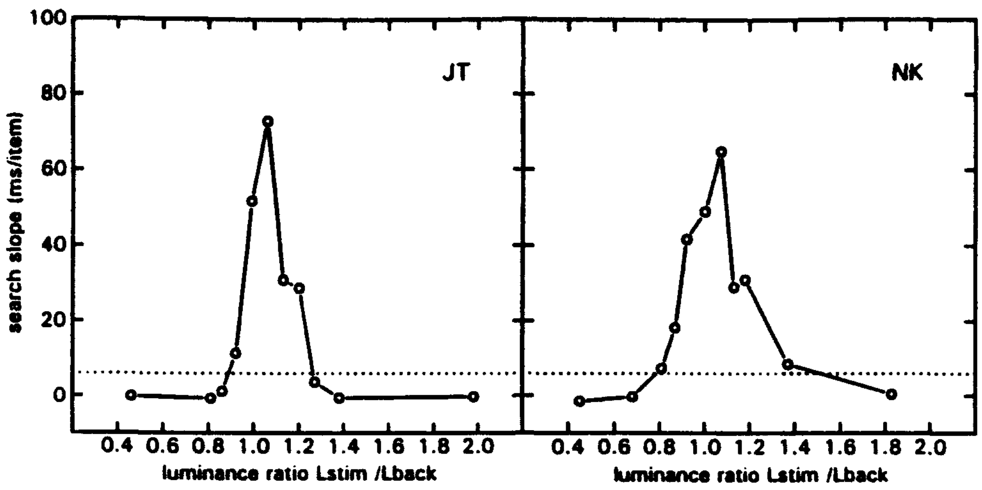

Fig. 2 Experiment 1: Search slopes as a function of the contrast ratio for observer JT and NK.

When a difference in luminance contrast is introduced, the search functions become flat indicating that the target element starts to pop-out. With small contrast ratios (between 0.8 and 1.2), search functions that can be thought of as mixtures of complete serial search, as found for the isoluminant condition (slopes of 20-80 ms/element), and complete parallel search (less than 6 ms/item) as found for the larger contrast ratios (less then 0.8 and more than 1.2). Such a mixture might possibly occur because only on *some* trials attention is captured by the target element. Alternatively, because the pop-out is relatively weak, attention might be attracted to an approximate area where the added item is located, requiring still some serial search to exactly locate the target.

3.2 Experiment 2

Table II gives the search slopes, the intercepts, and the error scores for Experiment 2. Figure 3 presents the slopes as a function of contrast ratio $(L_{circle}/L_{background})$. The longest search time is to be found at a luminance ratio of 1 because then the gray circles are identical to the background. In this condition, the stimulus field consists of isoluminant red line segments. The line segment that is added later obviously does not pop-out on a isoluminant background, a result that confirms the findings of Experiment 1. Figure 3 is comparable to Figure 2 suggesting that the pop-out observed in Experiment 1 is completely due to the difference in luminance and not to difference in color. Obviously, the pre-attentive system has no access to chromaticity information allowing the parallel detection of the added element.

Table II Experiment 2: Slopes, intercepts and error scores for the various contrast ratios ($L_{circle}/L_{background}$).

luminance contrast subject JT	intercept [ms]	slope [ms/element]	error score [%]	luminance contrast subject NK	intercept [ms]	slope [ms/element]	error score [%]
0.51	446	-0.41	8.9	0.51	540	-2.22	11.5
0.75	481	2.85	7.7	0.77	587	-0.72	7.7
0.85	587	5.01	6.4	0.83	592	7.17	9.0
0.89	441	57.22	1.2	0.90	657	21.06	6.4
1.00	543	67.77	12.8	1.00	568	36.89	5.1
1.07	749	43.62	3.8	1.07	469	26.84	10.2
1.15	511	14.19	9.0	1.14	623	15.2	9.0
1.21	531	3.21	7.7	1.23	566	7.5	9.0
2.01	481	2.22	10.2	1.36	508	1.86	15.4
				2.01	502	-1.28	10.2

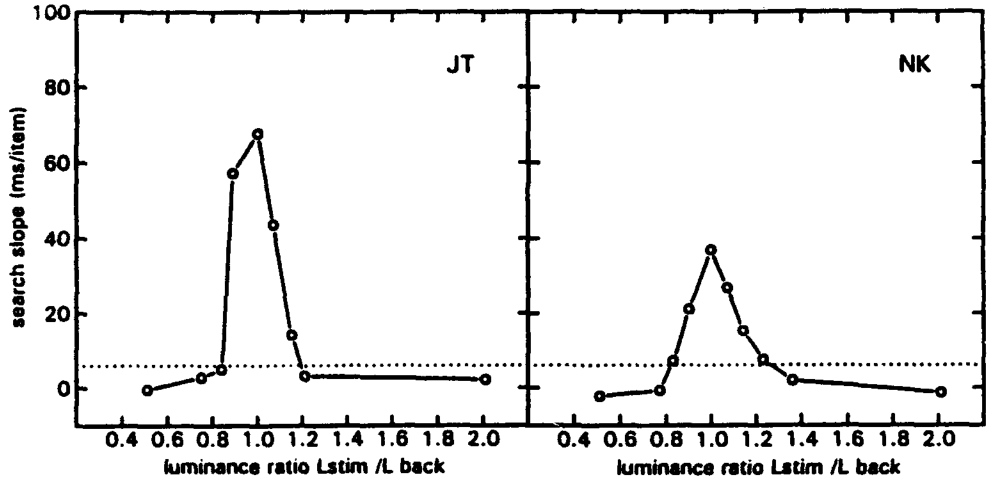

Fig. 3 Experiment 2: Search slopes as a function of the contrast ratio for observer JT and NK.

3.3 Experiment 3

The 100 ms display-to-target circle interval was included because it is possible that in Experiment 1 and 2 the target circle at isoluminance did not pop-out because it was presented with such a short interval. Kelly (1983) showed that there is little or no response for detecting red/green chromatic flicker beyond 15 Hz. The 50 ms interval used in Experiment 1 and 2 is equivalent to 20 Hz indicating that subjects may not have been capable of detecting the isoluminance color change because it was presented with an interval beyond the critical 15 Hz. In order to ensure that the absence of a pop-out at isoluminance is not due to limitations in the time domain (e.g., at 50 ms ISI, the target circle does not pop-out because it *appears* to be presented at the same time as the stimulus display) Experiment 3 with an ISI of 100 ms was included. The 100 ms interval is equivalent to 10 Hz which is clearly below the critical 15 Hz interval. Note that increasing the interval beyond 100 ms might result in chromatic adaptation which by itself will result in a pop-out of the target circle (Theeuwes & Lucassen, 1993).

Table III Experiment 3: Slopes, intercepts and error scores for the various contrast ratios ($L_{circle}/L_{background}$).

luminance contrast subject JT	intercept [ms]	slope [ms/ element]	error score [%]	luminance contrast subject NK	intercept [ms]	slope [ms/ element]	error score [%]
0.48	392	2.50	11.5	0.50	477	0.41	9.0
0.81	479	-1.26	6.4	0.82	499	2.50	7.7
0.89	480	-0.60	7.7	0.90	508	-1.25	7.7
0.95	464	13.02	5.1	0.96	544	2.10	5.1
1.0[illegible]	485	54.27	6.4	1.02	520	26.22	7.7
1.0[illegible]	671	15.78	7.7	1.09	611	23.19	11.5
1.16	523	11.63	11.5	1.16	437	27.27	10.2
1.23	502	6.29	6.4	1.23	620	-1.64	14.1
1.25	455	1.19	10.2	1.32	531	1.38	7.7
2.00	444	0.36	10.2	2.04	491	1.20	9.0

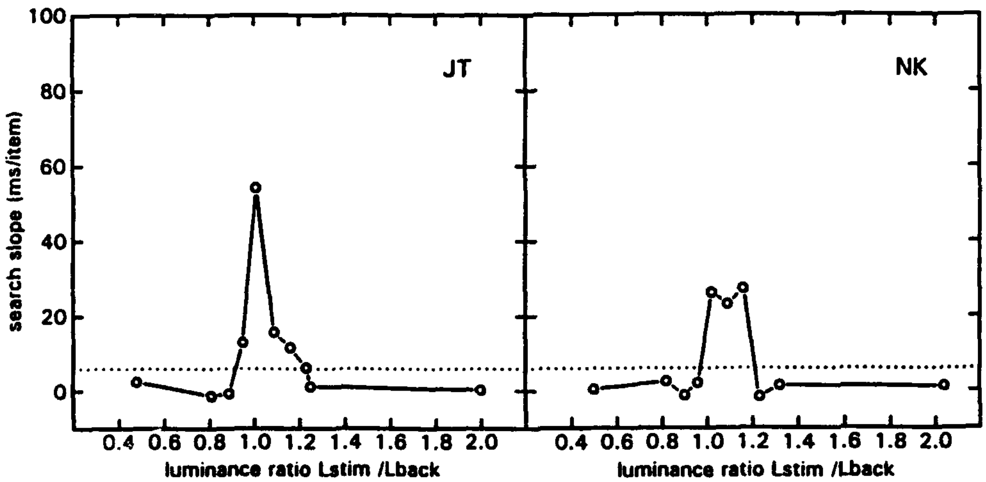

Fig. 4 Experiment 3: Search slopes as a function of the contrast ratio for observer JT and NK.

The results of this experiment are presented in Table III and Fig. 4. The longest search time is to be found at near isoluminance. The results are comparable to those obtained in Experiment 1 and 2 suggesting that a longer ISI does not change the overall pattern of results. The results indicate that the absence of a pop-out at isoluminance is not due to the limited temporal resolution for flickering chromatic stimuli as demonstrated by Kelly (1983).

4 GENERAL DISCUSSION

The present study was designed to examine whether isoluminant color changes can be detected in parallel. The results clearly indicate that this is not possible: even when observers are set to detect the color change they are unable to do so. Isoluminant color change obviously has no access to the pre-attentive system that can signal the presence of the added element. Experiment 3 shows that the isoluminant color change is not due to the fact that the stimulus field and target circle were presented in a fast successive order. The results indicate that the color change did not pop-out because it was presented at isoluminance with its background.

Failure to find a pop-out at isoluminance is in agreement with physiological findings. The relatively slow parvo-system which is concerned with processing of color information is not capable of triggering higher centers that something has changed. The data indicate however that a small luminance change is enough to trigger the luminance sensitive parvo system which immediately transmits signals to the brain, allowing the organism to orient and direct its attention to locations in visual space that potentially contain important information.

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The present study investigated whether an isoluminant color change pops-out indicating that it can be detected pre-attentively in parallel. Experiment 1 shows that an abrupt color change presented on an isoluminant background does not pop-out. However, when the color change is accompanied by a small luminance change, it pops-out and attracts attention. Experiment 2 shows that the pop-out is fully due to the luminance change and not to the color change. Experiment 3 shows that the failure to find a pop-out at isoluminance cannot be attributed to the limited temporal resolution for chromatic stimuli. The results are in agreement with physiological findings regarding the parvo and magno system.

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