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Luminosity—A perceptual “feature” of light-emitting objects?

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Abstract

Light-emitting objects are perceived as qualitatively different from light-reflecting objects, and the two categories elicit different cortical activity. However, it is unclear whether object luminosity is treated as an independent visual feature, comparable to orientation, motion or colour. Visual search tasks revealed that light-emitting targets led to efficient search when presented with light-reflecting distractors of similar luminance, but this efficiency was induced by the presence of luminance gradients producing the percept of luminosity rather than by luminosity itself. This implies that luminance gradients (not object luminosity) are encoded as features, questioning the existence of specific sensory mechanisms to detect light-emitting objects.

Keywords: Visual attention; Visual search; Brightness; Luminosity; Features

1. Introduction

Differing amounts of light coming from surfaces to the eyes can be produced either by changes in the level of illumination or by changes in the surfaces’ reflecting properties. At the retinal level it is assumed that such a distinction cannot be made, since only changes in luminous flux and spectral composition are present. However, information about illumination and reflectance is recovered by the visual system at the perceptual level allowing observers, for example, to distinguish easily between light-emitting objects (light sources or objects containing luminosity) and light-reflecting objects. Under typical daytime luminance conditions, most objects relevant to our actions reflect light. In contrast, light-emitting objects such as the sun are rarely of direct interest for object selection and subsequent action upon them. This raises the question of whether the visual system treats these two object categories (only distinguished at the perceptual level) in different ways, giving task-related priority to reflecting objects. Such an object-for-action based selection mechanism would make sense, considering that the optical salience of light-emitting objects often exceeds that of simultaneously present reflecting objects by several orders of magnitude. This enormous difference in luminance might capture attention if light-emitting objects were analysed by the same mechanism as reflecting objects, and thus cost important processing time for task-relevant objects.

If the perceptual distinction of light-reflecting and light-emitting objects is related to lightness and brightness, where lightness is defined as the reflectance of the surface of an object (ranging from black to white) and brightness as illuminance ranging from dark via bright to fluorescent and luminous/light-emitting (e.g. Gilchrist et al., 1999), reflecting objects should fall into the lightness category and light-emitting objects into the brightness category. Even though, at first glance, such a distinction seems simply to link physical and perceptual luminosity and reflectance, there are situations in which perceptual and physical information do not match: for example, most objects presented on a computer screen do not appear to emit light, even though in physical terms they do. Perceptually they fall into the lightness category, but physically they fall into the brightness category.

Worse still, if such assumptions are not just restricted to object properties (light-emitting versus reflecting), but also

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link perceptual phenomena in general to lightness and brightness scales, it would become almost impossible to distinguish perceptually between lightness and brightness effects on object selection: first, lightness and brightness scales largely overlap with exception of those ranges of the brightness scale in which dark would be 'blacker than black' (e.g. Vukusic, Sambles, & Lawrence, 2004) and bright would be 'whiter than white' (e.g. Bonato & Gilchrist, 1994); second, the interpretation of reflectance or illuminance strongly depends on the context of a task and observer expectations (Arend & Spehar, 1993a, 1993b).

However, accepting the above-mentioned identity of perception with lightness/brightness scales for the very specific case of object quality (light-emitting versus reflecting) implies that if the object categories of luminosity and reflectance are treated differently in tasks requiring object selection, they should rely on different neural mechanisms. For example, if the perceptual quality of luminosity were treated as a visual feature, usually thought to be restricted to sensory information directly linked to physical object parameters, this would imply that luminosity-specific neurons should exist.

Despite a vast literature on brightness and lightness phenomena, surprisingly little is known about their underlying neural mechanisms, and even less about the neural mechanisms underlying the perception of light-emitting objects, i.e. brightness perception within the limits of those scales which do not overlap with lightness when attributed to an object. The few functional imaging studies in humans that tried to identify the neural mechanisms of brightness perception revealed that while activity in V1 increased with luminance, it was insensitive to brightness induction (Boucard, van Es, Maguire, & Cornelissen, 2005). In contrast, intraparietal and lateral occipital sulcus seem to be sensitive to brightness illusions (Perna, Tosetti, Montanaro, & Morrone, 2005; Troncoso et al., 2005). Only one study so far provides evidence that luminosity in contrast to the entire brightness scale might be treated as a visual feature: a recent fMRI experiment identified an area in the occipito-temporal cortex adjacent or overlapping with area V8 that was selectively activated when fixating an object that was perceived as light-emitting (Leonards, Troscianko, Lazeyras, & Ibanez, 2005); this area might be involved in the perceptual distinction between light-reflecting and light-emitting objects, irrespective of the actual luminance of the object.

When trying to identify differential behaviour of light-emitting and light-reflecting objects it is important to establish whether the perceptual quality of luminosity, when isolated from accompanying luminance differences, is in itself sufficient as a basic visual feature. This study uses the visual search paradigm to address this issue. In visual search, subjects look for a target item among a number of distractor items. If the time needed to complete the search is roughly independent of the number of distractors, the search is said to be efficient; if the search time increases linearly with the number of distractors, the search is said to be inefficient (e.g. Leonards, Rettenbach, Nase, & Sireteanu, 2002; Wolfe, 2001). Elementary features of visual perception are generally agreed to be those which, provided the contrast between target and distractors with respect to this feature is high enough, elicit efficient search in naïve subjects (e.g. Treisman & Gelade, 1980, 1988). In other words, the target seems to "pop out" from the surrounding distractors. However, this criterion alone is insufficient to guarantee status as an elementary feature of visual perception: search for the presence of a basic feature (the feature is attached to the target) must also be faster than search for its absences (the feature is attached to the distractors but not the target) (see Wolfe, 2001, for definitions of basic feature requirements). Some examples of features isolated in this way by visual search are size, luminance or contrast, line orientation, colour and motion, line termination, and even complex features such as faces (Hershler & Hochstein, 2005). Search for targets containing features is thought to involve no or very few attentional resources, and it was referred to as pre-attentive in early publications on visual search (e.g. Treisman & Gelade, 1980; but see Joseph, Chun, & Nakayama, 1997). Targets for which a search is inefficient are thought to involve attentional resources (e.g. Bravo & Nakayama, 1992; Treisman & Gelade, 1980; Wolfe, 1998). Note that we use the terms 'efficient' and 'inefficient' in this manuscript to indicate that we make no assumptions about an underlying neural search processing mode, e.g. the presence or absence of spatial shifts of attention (for reviews on this issue see Chelazzi, 1999; Palmer, Verghese, & Pavel, 2000; Townsend, 1990). Only the efficiency of the search is important to identify feature characteristics. However, given that there is a continuum between efficient and inefficient search, it is important to set explicit criteria for the boundary between the two search types. We define efficient search not only in terms of flat search slopes for target present trials (e.g. of around 10 ms/item or less), but also in terms of the original feature-defining idea of a 'pop-out' search: specifically, a search is only really efficient if target absent trials have flat search slopes too. Note that such an assumption can be made only for studies using young, healthy participants; in elderly participants, feature search for target absent trials is often impaired, possibly due to increased cortical noise or changes in response strategy (Li, Lindenberger, & Sikstroem, 2001; Rush, Panek, & Russel, 1986). Testing elderly subjects would thus require additional controls to set up appropriate baselines for feature search processing.

If luminosity is a basic feature of visual perception, targets perceived as light-emitting should pop out when presented in the context of distractors perceived as light-reflecting of similar luminance contrast; conversely, light-reflecting targets should not pop out from light-emitting distractors.

2. Experiment 1: Pop out of light-emitting objects among light-reflecting distractors of similar mean luminance, but not vice versa

Experiment 1 was conducted to determine whether target stimuli perceived as emitting light pop out when presented amongst distractor stimuli which appear to reflect

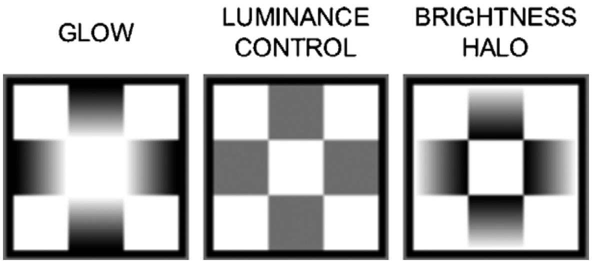

Fig. 1. Examples of items used in Experiment 1: glow, luminance control, and brightness halo. Note that for all three items the mean luminance of the elements was identical, but 'glow' was perceived as an object with a light-emitting (brightness enhanced) centre and 'brightness halo' was perceived as having a light-emitting, brighter ring surrounding it.

light. Search elements perceived as light-emitting, here called 'glow' stimuli, were based on a phenomenon first described by Kennedy (1976) and later used to produce stimuli for psychophysical investigations into lightness and brightness effects (e.g. Agostini & Galmonte, 2002; Zavagno, 1999) (Fig. 1): elements consisted of four squares (inducers), arranged to form a cross with a white central square gap (and four white corner square gaps). The luminance profile of the cross configuration contained linear luminance gradients from black (0.1 cd/m^2) in the periphery to white of the central white square (186.7 cd/m^2). It is this specific configuration of converging luminance gradients from dark in the stimulus periphery to bright close to its centre which produces brightness enhancement and results in the stimulus being perceived as being light-emitting (Zavagno, 1999; Zavagno & Caputo, 2001, 2005). Note that this is a purely perceptual ('illusory') phenomenon which can be produced on a piece of reflecting paper (see Fig. 1). It thus does not dependent on the physical light-emitting properties of a monitor. The four inducer squares for the 'luminance control' stimulus (Fig. 1) were a uniform luminance: the mean value of the luminance gradients used for the 'glow' inducers (93.4 cd/m^2). This meant that glow stimuli and luminance control stimuli had the same mean luminance, but the latter had no brightness enhancement of the central square and so did not seem to emit light (even though, being presented on a monitor, it physically did). A third stimulus (see Leonards et al., 2005) with inverted gradients served to distinguish between the effects of brightness enhancement (and use of gradients) per se and the particular effects of central brightness enhancement. This third stimulus contained luminance gradients from white in the periphery to black toward the centre, creating a 'brightness halo' around a centrally light-reflecting stimulus. In other words, the stimulus itself could be interpreted as reflecting while covering a light-emitting source behind it.

2.1. Method

2.1.1. Subjects

There were 22 participants (11 female), with an age range between 18 and 39 years (mean age: 21.9 years ±4.53*SD*). All participants had normal or corrected-to-normal visual acuity, and (with the exception of authors AC and UL) were naïve with respect to the purpose of the experiment. Experiments were undertaken with the understanding and written consent of each participant, and had been approved by the Ethical Committee of the Department of Experimental Psychology, University of Bristol.

2.1.2. Stimuli

Six types of stimulus were presented: (A) a glow target amongst luminance control distractors; (B) a luminance control target amongst glow distractors; (C) a glow target amongst brightness halo distractors; (D) a brightness halo target amongst glow distractors; (E) a brightness halo target amongst luminance control distractors; and (F) a luminance control target amongst brightness halo distractors. Stimuli were presented on an 18" LCD monitor with a 1024 × 768 pixel resolution on a mean luminance grey background (93.4 cd/m^2). Elements were arranged in a circle around the fixation cross (element centre to fixation cross: 7.3°; element size 1.4° × 1.4°); the element set size was either 6 or 12 elements.

2.1.3. Procedure

Subjects were comfortably seated with their head on a chinrest at a distance of 57 cm from the screen in an otherwise darkened room. The subjects' task was to indicate the presence or absence of a target by pressing as quickly and accurately as possible a button with their right index finger for target absence and another button with their left index finger for target presence. As soon as a button was pressed, the stimuli disappeared. Targets were present in half of the trials. If the subject did not respond within 5000 ms, the image disappeared and the trial was discarded. Subjects were allowed to move their eyes freely within trials, but were asked to fixate the fixation cross between trials. Subjects' reaction times and error rates were recorded.

Each subject performed an experimental session consisting of 3 blocks of 96 trials each, separated by short breaks. Every block contained two types of display variants randomly interleaved: displays of variants A paired with B, C paired with D, E paired with F. The block order was counterbalanced between observers. Each block was preceded by 30 practice trials to familiarise subjects with the new target and distractor sets and to give feedback about performance.

2.1.4. Analysis

Based on individuals' median reaction times (RTs), group mean RTs, search slopes (ms/item) and intercepts (ms) were calculated for each of the six target–distractor variants. Mean error rates were 3.2% ± 0.6*SEM* and did not differ across stimulus conditions. Only trials with correct responses were used. The processing time per item (slopes) allows the measurement of the costs for adding additional items to the display and therefore distinguishes between efficient search (flat search slopes) and inefficient search (steeper search slopes). The intercepts (where the search functions intersect with the y-axis), in contrast, might give insights into search-independent but stimulus-modulated processing stages. These might include early visual processing, inhibition mechanisms, competition in visual short-term memory, or general decision processes. Results were tested for significance with analyses of variance with repeated measures.

2.2. Results and discussion

In Fig. 2, the group mean RTs of subjects' median RTs are plotted for the six target–distractor search variants. Table 1 contains search slopes (ms/item) and intercepts (ms). Searching for a glow target within luminance control distractors (Fig. 2A) led to RTs (and search slopes—Table 1A) which were relatively independent of the number of distractors, implying an efficient search. Searching for a luminance control target within glow distractors (Fig. 2B, Table 1B), in contrast, was far less efficient, as indicated by an increase in RT for the bigger search set size. This fits with the hypothesis that 'search for the presence of a basic feature is more efficient than search for its absence' (Wolfe, 2001); thus, luminosity might have feature status. However, also the search for a brightness halo target within luminance control distractors was quite efficient (Fig. 2E; Table 1E), while

Table 1
Slopes and Intercepts for the six different target–distractor variants (Experiment 1): A, glow stimulus among luminance control stimuli; B, luminance control stimulus among glow stimuli; C, glow stimulus among brightness halo stimuli; D, brightness halo stimulus among glow stimuli; E, brightness halo stimulus among luminance control stimuli; F, luminance control stimulus among brightness halo stimuli

Conditions	Slopes (ms/item ± 1*SEM*)		Intercepts (ms ± 1*SEM*)	
	Target present	Target absent	Target present	Target absent
A	0.12 ± 2.17	12.59 ± 5.39	579 ± 26	595 ± 48
B	6.65 ± 4.44	25.01± 8.96	661 ± 63	712 ± 83
C	−8.14 ± 5.76	6.83 ± 8.81	912 ± 84	1136 ± 102
D	10.3 ± 5.79	27.15 ± 4.78	739 ± 55	969 ± 113
E	−1.52 ± 2.69	9.51 ± 4.37	618 ± 47	642 ± 44
F	4.03 ± 3.28	12.65 ± 4.24	658 ± 41	796 ± 73

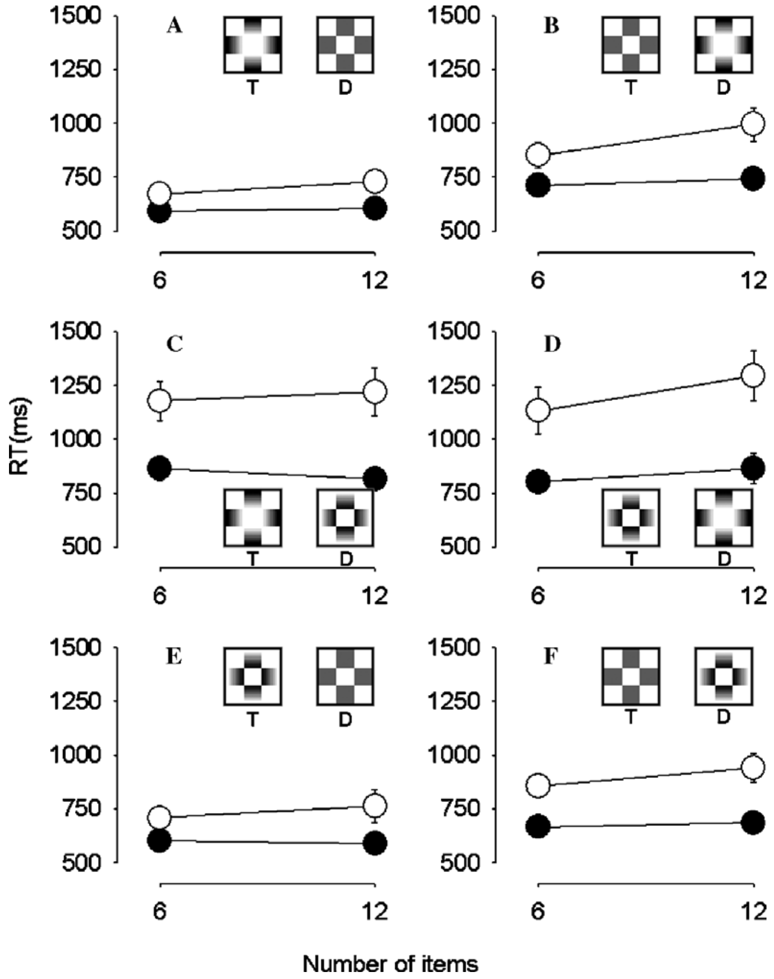

Fig. 2. Group means of subjects' median reaction times (in ms) for Experiment 1, plotted as a function of the number of items in the display. Filled symbols are trials with the target present; open symbols are trials with the target absent. Error bars are ±1*SEM*. Subjects searched for (A) a glow target amongst luminance control distractors; (B) a luminance control target amongst glow distractors; (C) a glow target amongst brightness halo distractors; (D) a brightness halo target amongst glow distractors; (E) a brightness halo target amongst luminance control distractors; and (F) a luminance control target amongst brightness halo distractors. For each condition, examples of targets (T) and distractors (D) are illustrated.

Table 2
Slopes and Intercepts for the eight different target–distractor variants (Experiment 2): A, glow stimulus among luminance control stimuli; B, luminance control stimulus among glow stimuli; C, darkness enhancement stimulus among luminance control stimuli; D, luminance control stimuli among darkness enhancement stimuli; E, darkness enhancement stimulus among darkness halo stimuli; F, darkness halo stimulus among darkness enhancement stimuli; G, darkness halo stimulus among luminance control stimuli; H, luminance control stimulus among darkness halo stimuli

Conditions	Slopes (ms/item ± 1*SEM*)		Intercepts (ms ± 1*SEM*)	
	Target present	Target absent	Target present	Target absent
A	2.84 ± 3.27	2.62 ± 5.77	606 ± 37	688 ± 68
B	6.52 ± 8.50	24.63 ±11.89	702 ± 106	743 ± 144
C	−0.58 ± 5.42	14.99 ± 4.75	696 ± 74	632 ± 49
D	11.87 ± 2.86	13.62 ± 6.1	621 ± 55	796 ± 75
E	−11.94 ± 6.20	24.19 ± 9.28	884 ± 74	861 ± 82
F	6.28 ± 6.13	20.56 ± 11.46	782 ± 99	816 ± 119
G	−5.5 ± 8.61	3.24 ± 5.66	848 ± 125	788 ± 94
H	16.23 ± 7.04	30.65 ± 8.67	718 ± 90	858 ± 101

searching for a luminance control target within brightness halo distractors was not (Fig. 2F; Table 2F). This seems to imply that luminosity need not be attached to the centre of the target as long as it is spatially attached (here 'behind' it). Furthermore, searching for glow targets within brightness halo distractors (Fig. 2C, Table 1C) or searching for a brightness halo target within glow distractors (Fig. 2D, Table 1D) required the longest RTs, both leading to relatively inefficient search and long intercepts, suggesting that glow and brightness halo were similarly salient.

A 6 (target–distractor variant) × 2 (number of elements) × 2 (target presence) ANOVA with repeated measures for reaction times revealed significant main effects for all three parameters: target–distractor variants ($F(5,100) = 12.25$; $p < .0001$); number of elements ($F(1,20) = 10.3$; $p < .005$); and target presence ($F(1,20) = 29.6$; $p < .0001$); as well as significant two-way interactions. *Post hoc* analysis for significant main effects of target–distractor variants confirmed that search for glow targets and search for brightness halo targets within luminance control distractors (conditions A and E) led to similar efficient search behaviour (*LSD* $p = .98$), but differed significantly from more inefficient searches for luminance control targets within glow distractors (condition B compared to condition A: *LSD* $p < .05$; condition B compared to condition E: *LSD* $p < .05$) and within brightness halo distractors (condition F compared to condition A: *LSD* $p < .01$; condition F compared to condition E: $p < .05$). Again, searches for luminance control targets were similar for both brightness distractor types (*LSD* $p = .62$). Searching for glow targets within brightness halo distractors (condition C) and vice versa (condition D) led to significantly longer searches than any other condition ($p < .00001$ to $p < .005$), and again the two searches did not differ significantly from each other ($p = .92$).

Thus, reaction time analysis for the first experiment indicates that the brightness enhancement induced by both the glow stimulus and the brightness halo stimulus permitted efficient searches when brightness enhancement was attached to the target within distractors of similar luminance but without brightness enhancement. When brightness enhancement was attached to the distractors, search was far less efficient. Moreover, given that glow and brightness halo stimuli led to similar results, it seems unlikely that central brightness enhancement was in any way special. However, according to our criteria, the common denominator of glow and halo stimulus, brightness enhancement, seemed to have feature status.

3. Experiment 2: Is there a difference between brightness enhancement and darkness enhancement?

The results of Experiment 1 indicate that it was the brightness enhancement that influenced targets and distractors differently, and that there was no difference between central and peripheral brightness enhancement. If we consider that in our peripheral brightness enhancement condition (the 'halo' stimulus) the actual light source seemed to be hidden behind an occluding object, it seems reasonable to conclude that, indeed, the object property luminosity was treated as a basic feature of visual perception as we predicted from previous fMRI experiments (Leonards et al., 2005). However, we cannot exclude that it is simply the brightness modulation in general and not luminosity that produced efficient search. If so, so-called darkness enhancement (black that seems to be blacker than black) should lead to similar search behaviour (see Fig. 3 for darkness enhancement in the centre of the stimulus ('darkness enhancement') and in its surround ('darkness halo')). This suggestion was tested in Experiment 2. Both darkness enhancement and darkness halo images had been used in an earlier fMRI study (Leonards et al., 2005) but did not lead to similar activation patterns to those elicited by the central light-emitting stimulus (here, the 'glow' stimulus).

3.1. Method

3.1.1. Subjects

Experiment 2 was performed with 12 participants (8 female), with an age range between 19 and 27 years (mean

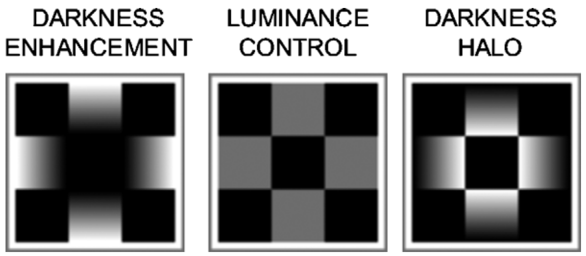

Fig. 3. Examples of items used in Experiment 2: darkness enhancement, luminance control for darkness enhancement, and darkness halo. Additional search trials contained the 'glow' and their respective 'luminance control' items as shown in Fig. 1. Note that for all three shown items, the mean luminance of the elements was identical, but 'darkness enhancement' was perceived as 'blacker than black' in the centre and 'darkness halo' was perceived as having a 'blacker than black' anulus around it.

age: 20.8 years ± 2.4*SD*). All other conditions were identical to Experiment 1.

3.1.2. Stimuli

There were eight stimulus types (see Fig. 3): (A) a glow target amongst luminance control distractors; (B) a luminance control target amongst glow distractors—note that both conditions A and B are identical to Experiment 1; (C) a darkness enhancement target amongst luminance control distractors; (D) a luminance control target amongst darkness enhancement distractors; (E) a darkness enhancement target amongst darkness halo distractors; (F) a darkness halo target amongst darkness enhancement distractors; (G) a darkness halo target amongst luminance control distractors; and (H) a luminance control target amongst darkness halo distractors. Stimulus presentation and size were identical to Experiment 1.

3.1.3. Procedure

The experimental procedure was identical to Experiment 1, except that subjects performed 4 experimental blocks. Each block contained two types of display, randomly intermixed: A paired with B, C paired with D, E paired with F, G paired with H. As in Experiment 1, block order was counterbalanced between observers. Each block was preceded by 30 practice trials to familiarise subjects with the new target and distractor sets and to give feedback about performance.

3.2. Results and discussion

In Fig. 4, the group mean RTs of subjects' median RTs are plotted for the eight target–distractor search variants, and Table 2 contains search slopes (ms/item) and intercepts (ms). As in Experiment 1, searching for a glow target within luminance control distractors (Fig. 4A, Table 2A) led to an efficient search, while searching for a luminance control target within glow distractors (Fig. 4B, Table 2B) was more inefficient. Similarly, searching for a darkness enhancement target among its corresponding luminance control distractors led to efficient search (Fig. 4C; Table 2C), whilst searching for luminance control targets within darkness enhancement distractors resulted in less efficient search (Fig. 4D; Table 2D). This shows very similar search behaviour for glow (conditions A and B) and darkness enhancement (conditions C and D). Indeed, *post hoc* analysis of a significant main effect for target/distractor variants ($F(7,70) = 8.8$; $p < .00001$) in an 8 (target/distractor variants) × 2 (element number) × 2 (target presence) ANOVA with repeated measure revealed that glow/darkness enhancement attached to the target led to shorter reaction times than when it was attached to the distractors (condition A compared to condition B: *LSD* $p < .0005$; condition C compared to condition D: similar trend with *LSD* $p = .07$) but did not differ significantly when comparing conditions with glow to the same conditions with darkness enhancement (condition A compared to condition C: *LSD* $p = .45$; condition B compared to condition D: *LSD* $p = .27$). Further, searching for a darkness halo target within luminance control distractors was efficient (Fig. 4G; Table 2G), while searching for a luminance control target within darkness halo distractors was not (Fig. 4H; Table 2H) (*LSD* $p < .0005$). So it was as inefficient to search for darkness enhancement targets within darkness halo distractors (Fig. 4E, Table 2E) as it was to search for darkness halo distractors (Fig. 4F, Table 2F) within darkness enhancement targets.

In other words, brightness and darkness enhancement led to more or less similar results: brightness or darkness enhancement compared to lightness facilitated visual search.

4. Experiment 3: Is it brightness enhancement or luminance gradients which induce efficient search?

In the first experiment, we found that search for targets with brightness enhancement attributes, irrespective of whether these were central glow or a glowing halo, was efficient when the target was embedded in distractors of similar luminance without a brightness enhancement attribute. The second experiment indicated that darkness enhancement produced similar results. One might therefore conclude that brightness/darkness enhancements are visual features. Both experiments, however, cannot exclude the possibility that the effects observed simply reflected the presence of the luminance gradients which were used as inducers. In other words, it might be the gradients, not the brightness/darkness enhancement that caused efficient search. To control for the effect of luminance gradients without attached brightness enhancement, we ran a third experiment in which we introduced a so-called 'scrambled' stimulus. This stimulus had identical luminance gradients to the glow stimulus of Experiment 1, but each inducer was rotated by 90° (see Fig. 5, scramble). Subjective reports of all participants confirmed that these scrambled elements indeed showed very little brightness enhancement.

4.1. Method

4.1.1. Subjects

This experiment was performed with 12 participants (8 female), with an age range between 18 and 39 years (mean age: 22.3 years ± 5.9 *SD*). All other conditions were identical to Experiment 1.

4.1.2. Stimuli

As in Experiment 1, six stimulus types were presented (Fig. 5): (A) a glow target amongst luminance control distractors; (B) a luminance control target amongst glow distractors; (C) a scrambled target amongst luminance control distractors; (D) a luminance control target amongst scrambled distractors; (E) a glow target amongst scrambled distractors; and (F) a scrambled target amongst glow distractors.

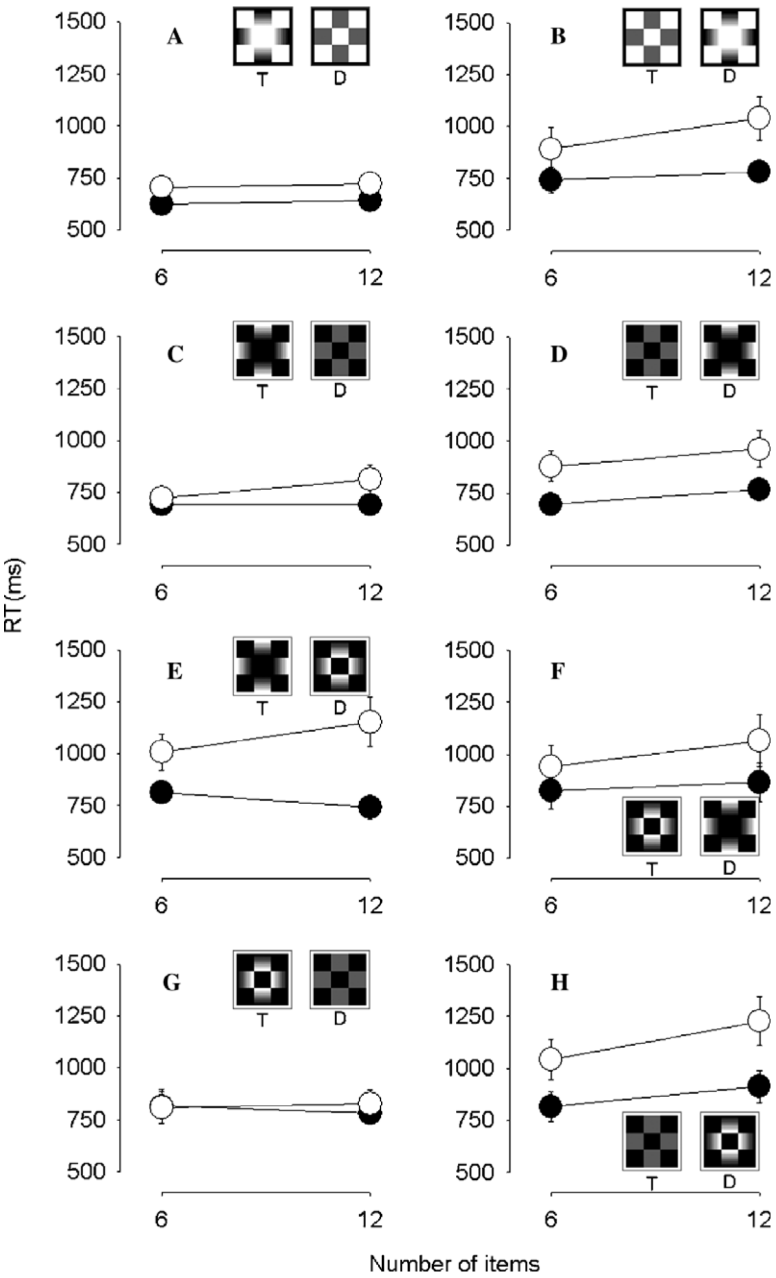

Fig. 4. Group means of subjects' median reaction times (in ms) for Experiment 2, plotted as a function of the number of items in the display. Filled symbols are trials with the target present; open symbols are trials with the target absent. Error bars are *SEM*. Subjects searched for (A) a glow target amongst luminance control distractors; (B) a luminance control target amongst glow distractors—note that both conditions A and B are identical to Experiment 1; (C) a darkness enhancement target amongst luminance control distractors; (D) a luminance control target amongst darkness enhancement distractors; (E) a darkness enhancement target amongst darkness halo distractors; (F) a darkness halo target amongst darkness enhancement distractors; (G) a darkness halo target amongst luminance control distractors; and (H) a luminance control target amongst darkness halo distractors. For each condition, examples of targets (T) and distractors (D) are illustrated.

Stimulus size, presentation, testing procedure and data analysis were identical to those described in Experiment 1.

4.2. Results and discussion

In Fig. 6, the group mean RTs of subjects' median RTs are plotted for the six target–distractor search variants, and Table 3 contains search slopes (ms/item) and intercepts (ms). As in Experiment 1, searching for a glow target within luminance control distractors (Fig. 6A, Table 3A), as well as searching for a luminance control target within glow distractors (Fig. 6B, Table 3B), led to very efficient and far less efficient search, respectively. *Post hoc* analysis of a significant main effect for target/distractor variants ($F(5,55) = 41.71$; $p < .00001$) in a 6 (target/distractor variants) × 2 (element number) × 2 (target presence) ANOVA with repeated measures revealed once more that this difference in reaction times for the two conditions was significant

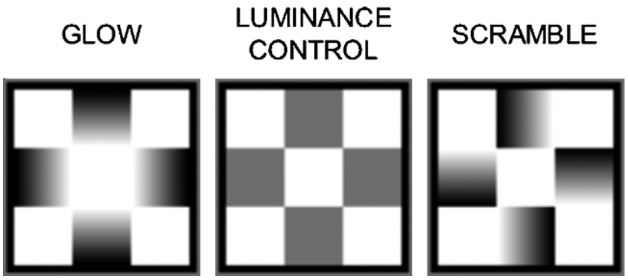

Fig. 5. Examples of items used in Experiment 3: glow, luminance control, and scramble. Note that for all three items, the mean luminance of the elements was identical, but 'glow' was perceived as an object with a light-emitting (brightness enhanced) centre, while the other two items were perceived as light-reflecting. Note further that scrambled contains the same luminance gradient inducers as 'glow', but each one is shifted 90° clockwise around the centre square.

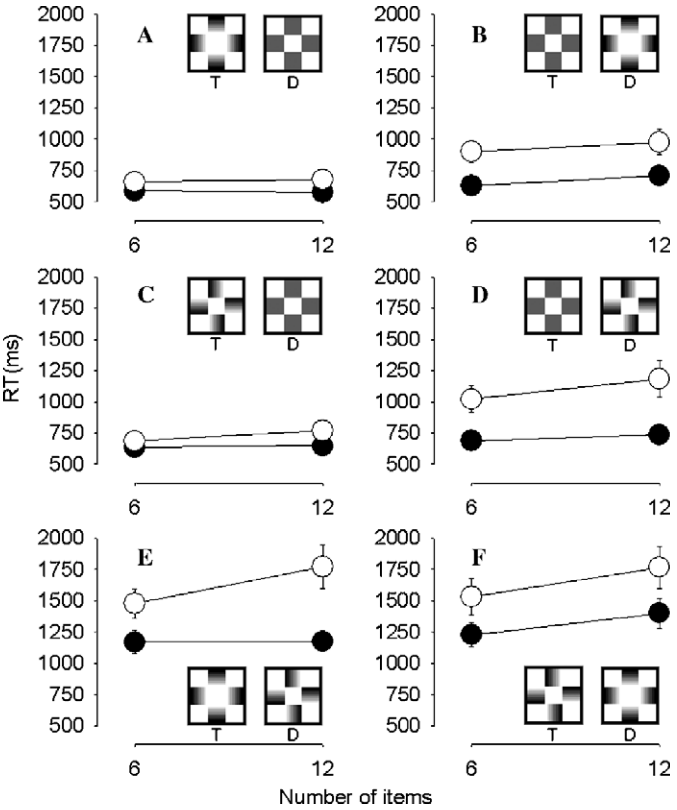

Fig. 6. Group means of subjects' median reaction times (in ms) for Experiment 3, plotted as a function of the number of items in the display. Filled symbols are rials with the target present; open symbols are trials with the target absent. Error bars are ±1*SEM*. Subjects searched for (A) a glow target amongst luminance control distractors; (B) a luminance control target amongst glow distractors; (C) a scrambled target amongst luminance control distractors; (D) a luminance control target amongst scrambled distractors; (E) a glow target amongst scrambled distractors; and (F) a scrambled target amongst glow distractors. For each condition, examples of targets (T) and distractors (D) are illustrated.

Table 3

Slopes and Intercepts for the six different target–distractor variants (Experiment 3): A, glow stimulus among luminance control stimuli; B, luminance control stimulus among glow stimuli; C, scrambled stimulus among luminance control stimuli; D, luminance control stimulus among scrambled stimuli. E, glow stimulus among scrambled stimuli; F, scrambled stimulus among glow stimuli

Conditions	Slopes (ms/item ± 1*SEM*)		Intercepts (ms ± 1*SEM*)	
	Target present	Target absent	Target present	Target absent
A	−1.5 ± 2.05	3.10 ± 4.18	594 ± 41	639 ± 53
B	13.25 ± 4.84	12.52 ± 9.71	549 ± 31	825 ± 102
C	2.03 ± 2.26	13.65 ± 3.85	621 ± 49	604 ± 48
D	7.51 ± 6.43	26.83 ± 8.16	645 ± 60	859 ± 74
E	0.93 ± 9.68	49.15 ± 14.94	1162 ± 138	1181 ± 109
F	28.79 ± 10.42	38.95 ± 9.85	1054 ± 112	1299 ± 149

(condition A compared to condition B: *LSD* $p < .05$). Searching for a scrambled target within luminance control distractors led to quite efficient search, and searching for luminance control targets within scrambled distractors was inefficient (Figs. 6C and D, Table 3C and 3D; condition C compared to condition D: *LSD* $p < .01$). Direct comparison of searches for glowing and scrambled targets within their respective luminance control distractors (condition A compared to condition C: *LSD* $p = .46$) or of searches for luminance control targets within glowing and scrambled distractors (condition B compared to condition D: *LSD* $p = .20$) showed that there is no significant difference in search behaviour for scrambled and glow conditions, thus confirming that it is not brightness enhancement per se, but the presence of luminance gradients which has an effect on search efficiency.

5. Experiment 4: Searching for lights at night

Under our experimental conditions, light-emitting objects were not treated differently from light-reflecting objects consisting of similar luminance gradients. However, before we can conclude from these data that, indeed, central brightness enhancement/luminosity is not a basic feature of visual perception, we might want to consider 'night time' conditions, under which light-emitting objects become far more salient and important. In a fourth experiment, we increased the perceived experience of luminosity by presenting the same stimuli used in Experiment 3, but this time using a minimum luminance background (instead of mean luminance) in an otherwise entirely darkened testing room. In other words, we increased the contrast between background and search elements and created a night-like search condition for light-emitting objects. This greatly increased the perceived luminosity of the glow search elements, but subjects still judged the luminance control stimulus and the scrambled stimulus as reflecting.

5.1. Method

5.1.1. Subjects

This experiment was performed with 12 participants (6 female), with an age range between 19 and 39 years (mean age: 22.0 years ± 5.54*SD*). All other conditions were identical to Experiment 1.

5.1.2. Stimuli

As in Experiment 3, there were six stimulus types: (A) a glow target amongst luminance control distractors; (B) a luminance control target amongst glow distractors; (C) a scrambled target amongst luminance control distractors; (D) a luminance control target amongst scrambled distractors; (E) a glow target amongst scrambled distractors; and (F) a scrambled target amongst glow distractors. Stimulus size, presentation, testing procedure and data analysis were identical to those described in Experiment 1.

5.2. Results and discussion

Fig. 7 shows the group mean RTs of subjects' median RTs for the six target-distractor search variants, and Table 4 contains search slopes (ms/item) and intercepts. As in Experiment 3, searching for a glow target within luminance control distractors (Fig. 7A, Table 4A) and searching for a luminance control target within glow distractors (Fig. 7B, Table 4B) led to efficient and inefficient search, respectively.

Table 4
Slopes and Intercepts for the six different target–distractor variants (Experiment 4): A, glow stimulus among luminance control stimuli; B, luminance control stimulus among glow stimuli; C, scrambled stimulus among luminance control stimuli; D, luminance control stimulus among scrambled stimuli. E, glow stimulus among scrambled stimuli; F, scrambled stimulus among glow stimuli; Note that this experiment was performed on a minimum luminance background

Conditions	Slopes (ms/item ± 1*SEM*)		Intercepts (ms ± 1*SEM*)	
	Target present	Target absent	Target present	Target absent
A	5.13 ± 4.95	13.61 ± 3.94	789 ± 81	768 ± 69
B	7.47 ± 3.96	30.60 ± 6.66	741 ± 62	787 ± 86
C	5.99 ± 4.26	9.70 ± 3.30	728 ± 42	773 ± 77
D	−0.02 ± 5.43	16.99 ± 6.86	821 ± 93	860 ± 76
E	17.69 ± 6.28	2.59 ± 7.43	817 ± 94	1106 ± 92
F	7.55 ± 4.53	36.15 ± 11.08	803 ± 54	882 ± 109

However, *post hoc* analysis of a significant main effect for target/distractor variants ($F(5,55) = 6.49$; $p < .0001$) in a 6 (target/distractor variants) × 2 (element number) × 2 (target presence) ANOVA with repeated measures revealed that

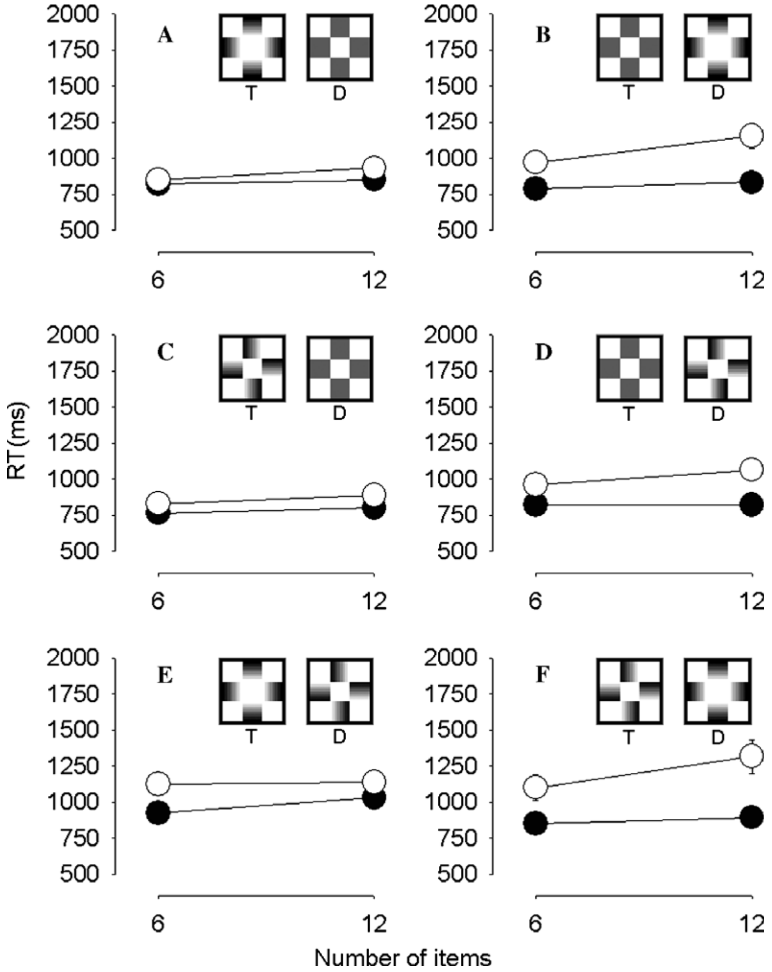

Fig. 7. Group means of subjects' median reaction times (in ms) for Experiment 4, plotted as a function of the number of items in the display. Filled symbols are trials with the target present; open symbols are trials with the target absent. Error bars are ±1*SEM*. Target–distractor combinations were identical to those used in Experiment 3, only this time items were presented on a minimum luminance background. Subjects searched for (A) a glow target amongst luminance control distractors; (B) a luminance control target amongst glow distractors; (C) a scrambled target amongst luminance control distractors; (D) a luminance control target amongst scrambled distractors; (E) a glow target amongst scrambled distractors; and (F) a scrambled target amongst glow distractors. For each condition, examples of targets (T) and distractors (D) are illustrated.

the difference in reaction times for the two conditions did not reach significance in this experiment (condition A compared to condition B: *LSD* $p = .16$), nor did searching for a scrambled target within luminance control distractors compared to searching for luminance control targets within scrambled distractors (Figs. 7C and D, Tables 4C and 3D; condition C compared to condition D: *LSD* $p = .068$). Direct comparison of searches for glowing and scrambled targets within their respective luminance control distractors (condition A compared to condition C: *LSD* $p = .42$) or of searches for luminance control targets within glowing and scrambled distractors (condition B compared to condition D: *LSD* $p = .72$) showed that there was no significant difference in search behaviour for scrambled and glow targets either. This confirms that it is the presence of luminance gradients but not brightness enhancement which has an effect on search efficiency (as shown in Experiment 3)—even under night lighting conditions and the subjective experience of almost unpleasantly strong light sources.

6. General discussion

The goal of the present paper was to investigate whether luminosity of an object can be considered as a basic feature of visual perception. A series of visual search experiments indicated that this is not the case: light-emitting targets were detected efficiently within light-reflecting distractors of similar global luminance but not vice versa, indicating that the light-emitting targets contained the important visual characteristic. However, control experiments revealed that this search efficiency was an artefact of the presence of the luminance gradients used to produce the perceived luminosity rather than of perceived luminosity itself. So, surprisingly, luminance gradients fulfilled the criteria for basic visual features, and none of the data pointed towards the encoding of brightness enhancement (or, in a control, darkness enhancement) as a feature.

The inability of luminosity to gain feature status seems surprising, given the qualitative difference in the perception of light-emitting and light-reflecting objects. Even though subjective reports from all subjects confirmed that the glow targets had been perceived as light-emitting, this information was not used to search more efficiently for light-emitting targets embedded in an array of distractor items with identical (but scrambled) luminance gradients. One reason for this failure to use luminosity as a feature might be that the contrast between luminosity and reflectance was not sufficient to produce efficient search. Indeed, as has been shown for colour and orientation (amongst many others), decreasing the feature contrast between target and distractors changes efficient into inefficient search (e.g. D'Zmura, 1991; Verghese & Nakayama, 1994). Specifically with the 'scrambled' stimulus, subjects might have had slight brightness induction effects between the lighter ends of the luminance ramps and the white background squares. However, such an explanation seems unlikely, since even the 'night condition' (in which the luminance contrast between background and search items was maximised, and in which subjects experienced light-emitting objects as almost unpleasantly bright in contrast to the light-reflecting 'scrambled' objects) failed to show any benefit for the detection of glowing targets.

Alternatively, perhaps the perceptual distinction of luminosity and reflectance in the absence of physical distinction (the stimuli were presented on a computer screen, and were therefore both physically light-emitting) takes time to build up, whereas a match between physical and perceptual distinctions does not. The high value of the intercepts in the search conditions in which all elements contained luminance gradients irrespective of whether they were targets or distractors (e.g. Experiments 1C and D) might be taken as evidence for this view. If this were the case, target selection (based on the arrangement of luminance gradients) might have been completed before the targets were perceptually light-emitting, yielding false negative results. Thus luminosity cannot necessarily be discounted as an elementary feature because physical light sources were not compared directly with physically reflecting objects of identical luminance. This suggests one direction for subsequent research.

If, on the other hand, the above-mentioned *caveats* are negligible, it can be assumed that luminosity is not a basic feature of visual perception. This implies that the visual system does not distinguish between objects represented within lightness or brightness scales, but uses one and the same mechanism for object selection. How might such a conclusion fit together with fMRI data indicating that an area in the occipito-temporal cortex adjacent or identical to area V8 is selectively activated when fixating an object that was perceived as light-emitting (Leonards et al., 2005)? One possible explanation is that the observed activation was not due to the existence of luminosity-sensitive neurons driven in a purely bottom-up (sensory) way, but reflected the interaction of top-down (context-dependent) and bottom-up (sensory driven) information processing.

Despite a qualitative difference between the perception of reflecting and light-emitting objects, object-bound luminosity does not appear to be a feature of visual processing and thus a building block of sensory (bottom-up) processing; luminance gradients, on the other hand, do appear to be features. This makes sense if the distinction between brightness and lightness is assumed to be a question of visual frameworks and not of individual objects (e.g. Gilchrist et al., 1999). To identify an object as light-emitting, its surround (including luminance gradients) must be taken into account, a process which requires time (pers. comm. Alan Gilchrist) and possibly top-down processing. As in so many areas of visual processing, it seems that context plays a key role.

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