The Effect of Objecthood on Processing Efficiency

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Abstract

The term objecthood is used to convey the degree of image regularity in terms of properties such as closure, symmetry and parallelism. The notion of objecthood is evaluated in the light of the existing psychological data on sensory-driven biases of attentional selection. Extending the biased competition for selection framework, we tested if higher objecthood of the image modulates its salience and exerts influence on the efficiency of its processing. In a series of three experiments, it is demonstrated that the presence of closure significantly impacts processing efficiency of the presented visual stimuli.

Keywords: vision; selective attention; saliency.

Introduction

Visual image regularities are important both for the interpretation of the ambiguous visual flow and for the guidance of selective attention resources for extensive analysis. Current understanding of bottom-up saliency underestimates the influence of these structural properties on the selection process. Most theories and models propose that regions compete for resources on the basis of their visual conspicuity. The aim of this paper is to demonstrate that it is the regularity of an image in terms of properties such as closure, referred to as its degree of objecthood, which determines its efficiency of processing and consequent selection, than merely its visual distinctiveness.

Due to the limited capacity of the visual system, only part of the information is selected for in-depth processing. It is important to direct resources towards regions that are potential figures because, first, usually they contain relevant information, and second, figures have invariant characteristics like shape, crucial for recognition, while the shape of the background varies depending on the figure and is meaningless (Rubin, 2001). It is generally accepted (Niebur & Koch, 1996; Itti & Koch, 2001; Desimone & Duncan, 1995) that selection operates on single features such as color, size and orientation, but they are not bound in any structure. The factor that guides attentional deployment and bias the selection of a region is its distinctiveness, defined by unique color, orientation or contrast, in comparison to the entire scene.

Although probably there is strong correlation between clusters of features and objects, we argue that what differentiates figures and backgrounds are qualitative differences. It has been extensively documented that the visual system makes use of various data regularities to constrain the possible combinations of elements and speed up the segmentation of the visual field into objects. These are the figural principles extensively investigated by Gestalt psychologists: size, closure, orientation, and contrast, symmetry, parallelism, convexity, meaningfulness (see Palmer, 1999 for a review), and lower region (Vecera, Vogel, & Woodman, 2002). They are highly unlikely to occur by chance (Lowe & Binford, 1982), so they are diagnostic for the presence of a figure in this location of the visual field.

However, the issue of whether such figural principles provide selection advantage and what is the mechanism that underlies it, has been left unexplored. Desimone and Duncan (1995) proposed that attentional selection is best understood as competition between all objects in the scene for cortical representation. Stronger, more salient stimuli have competitive advantage over weaker ones because they evoke more robust neural response. Although their account is mainly concerned with the physical distinctiveness of the stimuli, there is evidence that the degree of objecthood is still another factor that determines competitive strength. In the following section we will review behavioral data from visual search and object-based attention paradigms that one figural principle, closure, is associated with prioritized processing. Then, in a series of three experiments, we will examine further the nature and mechanisms of this competitive advantage.

Visual search task is a kind of task that requires serial scanning of a number of items for a particular feature. When the search is efficient, the target feature captures attention, the so-called pop-up, by virtue of its salience in comparison to the other items and the time to report it does not depend on the number of distractors (Treisman & Gelade, 1982). There is evidence that targets with particular non-accidental properties such as closure, pop out. Conci, Muller and Elliott (2007) reported that when participants were presented with search display that contains a target consisting of four corner junctions grouped by closure, and distractors containing the same four corner junctions but arranged to be open or semi-closed, the search performance for the target was unaffected by the number of distractors.

Similarly, Donnelly, Humphreys, and Riddoch (1991) showed that a combination of closure and collinearity yield flat search functions. Furthermore, Elder and Zucker (1993) demonstrated that search for brackets pointing in at each other among brackets pointing out is made easier if the brackets are clearly part of the same object. However, performance deteriorated when some of the distractors were also closed. Taken together, these findings speak in favor of the idea that items grouped by closure are more salient and have some competitive advantage.

Another line of evidence that favors the idea of objecthood as modulator of sensory-driven salience comes from attention literature. The "same-object benefit" refers to the faster and/or more accurate performance when two target properties to be identified appear in one object than when each of the properties appears in different object. This object-benefit seems to be a function of the nature of the region to which the target belongs. For instance, Marino and Scholl (2005) explored the time and accuracy when subjects compared targets that belong either to a cued rectangle or to a cued group of lines grouped by collinearity (rectangles that have their shorter borders removed). Although they found same-object benefit, the magnitude was reduced in the stimuli without closure.

Consistently, Watson and Kramer (1999) demonstrated that violation of closure diminishes the object-benefit effect. Subjects in these experiments viewed pairs of `wrenches' as stimuli, and had to decide from extremely brief (50 ms.) presentations whether the pair of wrenches contained both an open-ended wrench and a bent-end wrench. It was demonstrated that same-object benefit is obtained when the wrenches are uniformly connected, but not when there is discontinuity of color (the closure of the figure was violated).

To explain this pattern of performance, Watson and Kramer reside to Palmer and Rock's (1994) notion of uniform connectedness. The idea is that the entry level to visual perception constitutes of connected regions with homogenous properties such as contrast, color, texture, etc. These representations can be aggregated into larger units by principles of Gestalt grouping, or they can be decomposed into parts. It was argued (Watson & Kramer, 1999) that unless top-down factors induce a bias toward selection at a higher level, object-benefit effects are obtained when same-object targets belong to the same uniformly connected (single UC) region, but not when they belong to different single UC regions grouped into a higher order object (grouped UC regions). This is because a single UC regions involve a unified representation while shifting attention between grouped UC regions require shift of the representation as well which comes with a cost (Lamy & Egeth, 2002) and attenuate the same-object benefit.

However, this line of reasoning assumes that grouping is all-or-none phenomena and doesn't take the strength of grouping under consideration. It is plausible that the reported performance is a result of lowered competitive advantage of the object as a result of regularity violations of closure and continuity. The fact that closure had graded rather than all-or-none influence on object-benefit (Watson & Kramer, 1999; Marino & Scholl, 2005) favors this explanation. Comparison of the obtained magnitudes supports the idea that the presence of more non-accidental features is associated with greater magnitude of the same object benefit. For instance, Law and Abrams (2002) reported a same object benefit of 15 ms. when judging elements on a same or two different dashed lines. In contrast, realistic objects that contain much more information in terms of objecthood, yield magnitudes of 70 to 90 ms. (Watson & Kramer, 1999; Atchley & Kramer, 2001).

Furthermore, Kimchi (2000) demonstrated that uniform connectedness is not necessary characteristic of entry-level objects because elements organized according to the Gestalt laws of closure or/and collinearity are bound as early as the uniformly connected regions. In a similar vein, Han, Humphreys and Chen (1999) reported that Gestalt grouping by proximity is as fast and efficient as grouping by uniform connectedness.

To summarize, based on the review from visual search and object-based attention, it seems that selection (selective attention) is biased towards regions that are defined by closure. A parsimonious explanation of these findings is that these groupings are inherently more salient. For instance, Roelfsema (2006) proposed that there are excitatory connections between neurons that code features of the same objects to ensure that they are co-selected for perception and action. On the other hand, the connections between features that are not grouped are inhibitory which degrades their representations. So, while grouping strengthens the cortical representation of the objects, segmentation weakens it. Similarly, Carrasco and McElree (2001) reported that data-driven selection is mediated by accelerated rate of processing information. Therefore, it seems that the saliency of the strong objecthood regions resulted from their increased processing efficiency. More specifically, elements belonging to a group with stronger objecthood will participate more rigorously in the operations of the system, yielding accelerated rate of processing and biasing selection towards them.

Although there is evidence that closure is processed preferentially, none of the existing experiments have explicitly tested the assumption that *this sensory-driven bias is a result of the stronger groups being processed more efficiently than weaker groups*. We carried out a series of experiments that directly assess the validity of this proposal. This hypothesis is based on the general cognitive architecture DUAL where each group is represented by a coalition of agents and the coalition may be stronger or weaker. Depending on the strength of the coalition the efficiency of processing (η) is changed and determines the speed of processing of the information in that coalition (Petrov & Kokinov, 1999). In Experiment 1 we tested whether systematic alternation of closure will result in attenuation of the object-benefit in two target judgments. In

Experiment 2 we assessed if the presence of closure will affect the processing of a single target. In Experiment 3, we pursue to explore further the nature of the representations that mediate the sensory-driven bias.

Experiment 1

Based on the assumption that stronger objecthood yields accelerated rate of processing, two equally separated targets will be processed faster and more accurately when embedded in figure with stronger objecthood. The paradigm used is close to that employed in object-based attention literature. However, instead of presenting two figures, we presented a single one in order to explore the same-object advantage as a function of the nature of the object. The rationale is that altering objecthood by removing the property of closure will impede the processing of the targets.

Method

Design

The experiment used a within-subjects design. The independent variable was the objecthood of the figure which has two levels: strong (closed rectangle) and weak (rectangle without closure). The dependent variables were the RT and accuracy for speeded judgment of identity similarity. There were 32 unique displays presented 7 times each. All factors were counterbalanced and presented randomly. The distance between the target dots was identical in both conditions.

Stimuli

Stimuli were created after these used by Kimchi (2000) to make sure they are bound sufficiently quickly. Two groups of stimuli were designed for each condition. The strong objecthood figure constitutes a rectangle of size 200x200 pixels. The weak objecthood constitutes a rectangle of the same size from which an equal amount of contour (100 pixels) was removed around the corner junctions to prevent grouping by closure. The fixation point and rectangles were black on a white background. The target was a pair of dots with diameter of 9 pixels that can be either same identity (black/white) or different identity (black/white) that were centered on two adjust sides of the figures (A and B in Figure 1).

A B C D E

Figure 1: Examples of target stimuli: Weak (A) and strong (B) objecthood condition in Experiment 1, weak (C) and strong (D) objecthood condition in Experiment 2, strong (D) and weak (E) objecthood condition in Experiment 3.

The fixation point was a cross which subtended about 0.5° x 0.5°. Each rectangle subtended about 9° x 9° with a stroke of 0.1°. The target dots constitute a circle with angular size of 0.45°. The black target dot was filled while the white target dot had white center and black outline with a stroke of 0.1°

Procedure

The subjects sat without head restrain approximately 60 cm from the monitor. Each trial began with blank screen for 500 ms. The fixation cross then appeared for 400 ms., followed by the target stimulus presented for 250 ms. Afterwards, a mask appeared until the participant responded (Figure 2).

Participants were instructed to perform a discrimination task by pressing button 1 on the button box when the identity of the two dots is the same and button 3 when the identity is different. Subjects were asked to maintain fixation throughout each trial and respond as fast as possible while minimizing errors. There was one experimental block of 224 trials selected randomly, different for each subject.

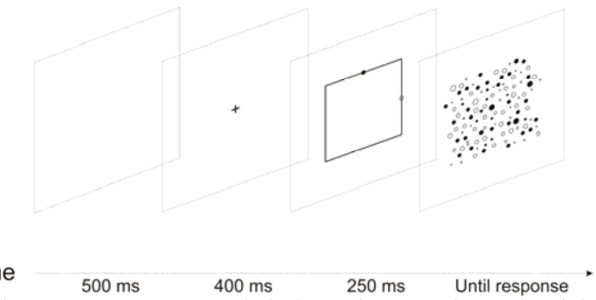

Figure 2: Sequence and timing of events in each trial: blank screen, fixation, target stimulus, and a mask.

Apparatus

The experiment was designed and run using E-prime Software (Version 1.1, Psychological Software Tools, 2002). A personal computer with Pentium III processor controlled the stimulus display. Monitor resolution was 1024x768, screen refresh rate was 85 Hz.

Participants

The subjects were 6 female and 9 male naïve volunteers. Their age varied from 19 to 29 years old. They were recruited in the campus of New Bulgarian University, Sofia. All reported normal or corrected-to-normal vision.

Results and Discussion

Results are displayed in Table 1. Mean accuracy rates for experiment 1 were: strong objecthood= .95, weak objecthood=.88. There was significant effect of objecthood [$t(14)=8.45$, $p<.000$]. Median RTs from correct trials were calculated for each participant in each of the conditions: strong objecthood= 422 ms. (SD=82), weak objecthood=441 ms. (SD=80). A paired samples t-test tested the effect of objecthood with median RTs as a dependent variable. There was significant effect of objecthood [$t(14)=-1.17$, $p<.001$]. Participants were significantly faster at judging the similarity when the targets were embedded in strong objecthood figure than in weak objecthood figure (422 ms. vs. 441 ms.).

Although the experimental manipulation significantly influences target processing, the results are ambiguous to whether the facilitation in the strong objecthood condition is due to the ease of shifting attention within a more strongly grouped representation or to the general increase in processing efficiency of the object-representing coalition. We explored further this issue in Experiment 2.

Table 1: RT and accuracy for Experiments 1, 2, and 3. The asterisk indicates statistically significant difference p>.05 between experimental conditions.

	Target			
	Strong Objecthood		Weak objecthood	
	M	SD	M	SD
	Experiment 1			
RTs	422*	82	441*	80
% Correct	95*		88*	
	Experiment 2			
RTs	310*	78	322*	80
% Correct	98		97	
	Experiment 3			
RTs	304*	63	315*	60
% Correct	98		97	

Experiment 2

Lamy and Egeth (2002) argued that same-object comparisons of two targets are facilitated because they involve shifts of attention within single representation while different-objects judgments also need shift of attention from one representation to the other that results in higher processing load and consequent decrease in performance. We didn't address the nature of comparisons between groups, though one might argue that the worse performance in the weak objecthood condition is due to slower shift between the separate lines that are two separate representations while the uniform rectangle is perceived as a single representation and the shift comes at almost no cost. However, this interpretation is not consistent with our proposal of the mechanisms behind the competitive advantage of strongly grouped regions. In our account, the observed difference in performance is due to more general increase in processing efficiency and therefore in the speed of processing. More specifically, we expect that performance will be better in the strong objecthood condition even when the experimental task requires identification of a single target.

The background figures were identical to Experiment 1 while the imbedded target was a single dot to rule out any explanation of the results in terms of attentional shifts.

Method

Design

The independent variable was objecthood of the figure which has two levels: strong (closed rectangle) and weak (rectangle without closure). The dependent variables were the RT and accuracy for speeded judgment of identity (white vs. black). There were 16 unique displays presented 14 times each.

Stimuli

Same as in Experiment 1 except that only a single dot was present as target (See C and D in Figure 1).

Apparatus and Procedure

Same as in Experiment 1.

Participants

The subjects were 12 female and 8 male naïve volunteers. Their age varied from 20 to 27 years old. They were recruited in the campus of New Bulgarian University, Sofia. All reported normal or corrected-to-normal vision.

Results and Discussion

Results are displayed in Table 1.Mean accuracy rates for experiment 2 were: strong objecthood= .98, weak objecthood=.97. There was no significant difference between d' values in the different conditions (p>.05). Median RTs from correct trials were calculated for each participant in each of the conditions: strong objecthood= 310 ms. (SD=78), weak objecthood=322 ms. (SD=80). A paired samples t-test tested the effect of objecthood with median RTs as a dependent variable. There was significant effect of objecthood [t(19)=3.6, p<.003]. Participants were significantly faster at discriminating the targets when the targets were embedded in strong objecthood figure than in weak objecthood figure (310 ms. vs. 322 ms.).

Although the results rule out any explanation of objecthood benefit in terms of shifting attention, between representations, there is still possibility that the results are due to some alternative mechanism other than the competitive advantage of the strongly grouped region. For instance, if the elements in the weak condition were not bound together, the higher RTs may be due to serial exploration of each representation, or alternatively, some crowding effect (Ehlers, 1936), that is the mutual inhibition of elements when competing with each other (Desimone & Duncan, 1995). In Roelfsema's (2006) proposal, grouped elements mutually excite each other while there is inhibition between elements perceived as separate. So, while grouping strengthen the cortical representation of the objects, segmentation weakens it leading to worse performance. Experiment 3 seeks to explore further if this pattern is due to accelerated processing in terms of saliency of the stronger group or to impeded processing of the weaker group due to crowding effects. Additionally, it aims to clarify whether any binding of the lines was present to affect performance.

Experiment 3

The purpose of Experiment 3 was to examine possible alternative interpretations of Experiments 1 and 2. For instance, except of the stronger objecthood condition (uniform rectangle) in Experiment 1 and 2, the rest of the conditions involved background figures formed of separate lines arranged according to some grouping principle, grouped uniformly connected regions in the terms of Palmer and Rock (1994). In case of absent binding, it could be argued that difference in performance is unrelated to the objecthood of the figure. Rather, the competition between the separate lines compromises the representation of the target. To rule out this account, in Experiment 3 we presented subjects with a single background line and compare performance with that in the condition with the uniform rectangle. If the difference in performance remains, this would further confirm our interpretation in terms of increased processing efficiency.

Method

Design

The independent variable was objecthood of the figure which has two levels: strong (closed rectangle) and weak (a single line). The dependent variables were the RT and accuracy for speeded judgment of the dot identity (white vs. black). 16 unique displays were presented 10 times each.

Stimuli

Same as in Experiment 2 except that the weak objecthood condition was a single line (See D and E in Figure 1).

Apparatus and Procedure

Those reported in Experiment 1.

Participants

The subjects were 8 female and 12 male naïve volunteers. Their age varied from 19 to 26 years old. They were recruited in the campus of New Bulgarian University, Sofia. All reported normal or corrected-to-normal vision.

Results and Discussion

Results are displayed in Table 1. Mean accuracy rates for experiment 3 were: strong objecthood=.98, weak objecthood=.97. There was no significant difference between d' values in the different conditions ($p>.05$). Median RTs from correct trials were calculated for each participant in each of the conditions: strong objecthood= 304 ms. (SD=63), weak objecthood=315 ms. (SD=60). A paired samples t-test tested the effect of objecthood with median RTs as a dependent variable. There was significant effect of objecthood [$t(19)=3.0$, $p<.007$]. Participants were significantly faster at judging the identity of the targets when the targets were embedded in strong objecthood figure than in weak objecthood figure (310 ms. vs. 322 ms.).

The results support that existence of competitive advantage due to stronger objecthood. Target was identified more efficiently when embedded in a rectangle than in a simple line. This is a very curious finding since the line possesses 1/8 of the pixels of the rectangle. The data ruled out any explanation of the results from experiment 1 and 2 in terms of crowding effects because even with a single background line, the difference between the two conditions remains.

Discussion

In three separate experiments it was demonstrated that objecthood modulates target processing performance. Although the data is inconclusive regarding whether separate lines in the weaker objecthood conditions were grouped at all, the almost identical magnitude of strong objecthood benefit in experiment 2 and Experiment 3 (12 ms. vs. 13 ms.) favors this interpretation. It seems that the other lines, besides the one that contained the target, were not processed at all in Experiments 1 and 2, as one might expect any deterioration of performance in comparison to Experiment 3 due to the crowding effect. Unless the elements are not grouped to collaborate with each other, there is mutual inhibition and the degradation of the representations of all of them (Chelazzi & Desimone, 1999). In the terms of biased competition for attention account (Desimone & Duncan, 1994), the goal (the target dot) served as effective top-down bias to discard the irrelevant information and process only the relevant that is the elements that contained the target. Even though the background figure itself was completely irrelevant to the task, it seems that the dot is obligatory assigned to it.

This raises the interesting issue of what constitutes an object for the selection process. The results of our experiments are in agreement with Palmer and Rock (1995) that the entry-level representations are uniformly connected regions such as the rectangle and the single line. In fact, the stimulus material was designed as such, so the dot is unambiguously perceived as intrinsic part of the object and both are presented at the same time to further strengthen this impression which probably determines their obligatory binding. On the other hand, as Watson and Kramer (1999) noted, the grouping of the unconnected lines is optional and depends on top-down influences such as strategic advantage. For instance, Marino and Scholl (2005) found object-based benefit for lines grouped by proximity, but they used a predictive cue to bias attention to one group or another, so the grouping was beneficial for performance and may be induced by top-down pressure. Similarly, in visual search tasks elements grouped by closure bias the selection but there was top-down template for the target that could have induced the grouping (Donnelly et al, 1991).

We designed the stimuli based on the findings of Kimchi (2000) that connected and disconnected rectangles provide comparable priming effects even at short presentations of 40 ms., indicating the presence of grouping. Although the study employed control for priming induced by unorganized lines, we failed to replicate the findings probably because the two tasks tap different mechanisms. For example, Kimchi's task was shape judgment which may have induced strategic grouping by task-driven pressure. In our case, the grouping of elements was uninformative for the location of the target as all the possible combinations were presented randomly, so the top-down information that contains the task description probably doesn't contain any information about the background figure that can induce higher-order binding of unconnected elements.

Regarding our major hypothesis that objecthood affects the saliency of a target and the efficiency of its processing, the results from two different experimental tasks: color naming and color discrimination, support it. However, objecthood seems to be calculated on the basis of uniformly connected regions when any top-down influence for higher level grouping is absent. However, there are some theoretical disagreements between Palmer and Rock's account and ours. For instance, they proposed that uniformly connected regions gain the status of representations after the figure-ground segregation is finished. On the contrary, we argue that the computed objecthood of the uniformly connected regions determines figure-ground segmentation by increasing the bottom-up salience of the more figure-like region. For instance, in our account, the figural status of regions characterized by non-accidental properties stems from their computational advantage and earlier selection.

If this assumption is valid, one might expect that attending purposefully to a region that is less figure-like, will grant it a figural status as top-down selective attention and bottom up-saliency trigger similar cortical mechanisms (Plaux & Egeth, 2007). In fact, Baylis and Driver (1995) reported such findings, but mere bottom-up capture of attention by a cue with sudden onset is ineffective in reversing natural figure/ground segmentation. In other words, physical distinctiveness cannot override the competitive advantage of the objecthood factors.

However, we did find that a background rectangle with more pixels provided competitive advantage over a line and this may be attributed to differences in visual distinctiveness. If so, we would expect influence of salience to enhance the processing of the target in conditions where there were four lines in comparison to only one, which is not the case. Though it might be that contrast of a region accelerates its processing, it comes to play only when the target is bound to this region. Further studies should control for the number of pixels while varying the grouping factors.

In conclusion, the feature-based selection is unable to explain why some properties such as closure bias the selective process in a bottom-up manner. So, the proposed approach seems fruitful to provide new insights into the remarkable efficacy of the human visual system. Note, however, that these are preliminary data and have to be interpreted with caution. Additionally, more research is needed to confirm that other grouping factors besides closure, affect processing efficiency, so the construct of objecthood can be further supported.

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