Effect of local fluency gradient of objects creates search asymmetry

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Abstract

Search asymmetry is a phenomenon in which search efficiency in a visual-search task differs for searching for an X target among Y distractors from search for a Y target among X distractors. Previous research shows that search asymmetry is mainly produced by a difference in the whole signal strength of items or a difference in item familiarity. This study reports that a difference in the local fluency within items also affects search efficiency and generates search asymmetry. Fluency is a value that correlates with the processing efficiency of an item. In particular, five experiments reveal that search efficiency for two part items depends on whether a fluent part is the top or bottom portion of a target (vs. distractor). We argue that this type of search asymmetry implicates the operation of an unknown mechanism that detects local fluency gradient in visual processing.

Keywords Eye movements and visual attention · Visual search

Visual-search tasks are widely used for research in visual attention (Treisman & Gelade, 1980). In a typical task, participants are asked to search for a target among distractors, and the time required to detect a target (referred to as reaction time, RT) is measured. The main result is obtained by calculating search functions in which mean RTs are plotted as a function of the number of items in a display (i.e., the number of distractors in target-absent trials and the number of distractors plus the number of a targets in target-present trials). Typically, RT increases linearly with the number of items. Thus, the slope of the linear regression of the search function is considered an index of visual search efficiency (Wolfe, 1998). When slopes are shallow, a search is deemed efficient; that is, a target is quickly detected.

The phenomenon known as search asymmetry has played an important role in understanding the mechanisms of visual search. Search asymmetry occurs when two types of items (X and Y) are used in a visual-search task. Search efficiency differs when the task requires searching for an X target among Y distractors versus searching for a Y target among X distractors (Wolfe 2001). When searching for an X among Ys is faster than searching for a Y among Xs, X is said to have

greater salience strength than Y. Although it is established that search efficiency depends on both the similarity between a target and a distractor and similarities among distractors (Duncan & Humphreys, 1989, 1992), search asymmetry involving the same set of items reveals a difference in search efficiencies between these conditions that is not consistent with a similarity-based account of search efficiency. This suggests the operation of unique factors not directly related to interitem similarity in search asymmetries.

Two factors have been involved in search asymmetry. One factor, involves a target search for a specific feature among distractors lacking this feature, as described by Treisman and Gormican (1988). This type of search is faster than a search for a target lacking the specified feature among distractors with this feature. For example, in a search using two types of items (a circle plus a line segment “Q” and a circle “O”), the search for a Q among Os is faster than that for an O among Qs. Treisman and Gormican attributed this asymmetry to a difference in the whole physical signal strength between two items. Since Q has an additional line segment compared with O, Q has the stronger physical signal. In addition, these researchers assumed that attention is guided by relative strength of signal of an object. Consistent with this assumption are findings that target–distractor pairs with different signal strengths (e.g., a bright item among dark items) also reveal search asymmetry. Thus, these results can be generalized as follows: If there are two types of items distinguished by their relative whole-signal strength in a visual-search task, inverting their role (target or distractor) should make a difference in the

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search efficiency (Treisman & Gormican, 1988; Wolfe, 2001). We refer to this effect as the “whole-signal strength” effect.

In addition to the whole-signal strength effect, a second factor affecting search efficiency concerns participants’ familiarity with search items (Wang, Cavanagh, & Green, 1994). For example, a target is more efficiently searched when a normal image of an alphabetical character (familiar item, e.g., “N”) is the distractor and its mirror image (unfamiliar item) is the target than when these roles are reversed. Wang et al. (1994) suggested that novelty (unfamiliarity) is calculated in the preattentive process, thus leading automatic guidance of attention to a location with a novel item; the result is that search asymmetry occurs when a target and a distractor differ in familiarity. On the other hand, many argue that search asymmetry largely occurs whenever processing of an unfamiliar object requires more time than processing a familiar object. In other words, efficiency depends on whether the distractors that require more processing than the target are familiar to participants (Malinowski & Hübner, 2001; Shen & Reingold, 2001; Wolfe, 2001). Here, we do not discuss the validity of these hypotheses; rather, we note that previous studies have repeatedly confirmed the generality of search asymmetry between two items differing in familiarity (Malinowski & Hübner, 2001; Wolfe, 2001). We refer to this as the “familiarity effect”.

The current study seeks to discover a type of search asymmetry that is not explained by these two factors. A careful review of previous studies revealed clues to a novel type of search asymmetry. Logan (1994) investigated the positional relationship between parts constituting an item. To this end, he used items consisting of two parts (plus “+” and minus “−”) vertically aligned in a visual-search task (e.g., “±” and “∓”). One item was a target, the others distractors. Logan discovered that search slopes varied depending on which type of vertically aligned configuration was the target. Both items (“±” and “∓”) consisted of the same parts, hence had the same (whole) signal strength. Therefore, the whole-signal strength effect cannot explain the asymmetric pattern in visual-search performance. On the other hand, the familiarity effect might influence on the result because “±” is more often used in mathematics than “∓” is. In fact, in their experiment, the search slope was shallower when “∓” was the target than when “±” was the target.

Nevertheless, we hypothesize that familiarity does not shape the asymmetry effect. Specifically, in paying attention to parts of an item, we observe that “+” has stronger signal than “−” because the former has more segments than the latter. Thus, there should be search asymmetry in which searching for “+” among “−” is faster than searching for the converse. That is, “+” has higher saliency strength than “−” does. In other words, there is a vertical difference in saliency strength distribution within each of the “±” and “∓” items. If this holds, we can hypothesize that search asymmetry occurs when there

is a saliency strength gradient within items. This is termed the “local saliency strength gradient effect” hypothesis.

Another explanation based on the suggestion by Treisman and Gormican (1988) and Chang and Mitchell (2009) is also possible. They pointed out that larger values on a quantifiable dimension (such as size) could mark the presence of a feature that allows larger stimuli to be discriminated more easily from smaller stimuli than smaller stimuli to be discriminated from larger ones. They suggested that this could be because an object with a strong signal might be processed faster than an object with a weak signal. That is, “+” has higher processing fluency than “−” does. In other words, there is a vertical difference in fluency distribution within each of the “±” and “∓” items. If this holds, we can also hypothesize that search asymmetry occurs when there is a fluency gradient within items. This is termed the “local fluency gradient effect” hypothesis.

Five experiments were conducted to test these hypotheses. The goals of the first three experiments were to identify the type of search asymmetry caused by a novel factor in the local saliency strength gradient (or local fluency gradient). We used two variations of an item consisting of two parts with different saliency strengths (fluency) by preparing two search items. One search item consisted of an upper part with high saliency strength (high fluency) and a lower part with low saliency strength (low fluency), whereas the other item consisted of an upper part with low saliency strength (low fluency) and a lower part with high saliency strength (high fluency). There were two conditions: One item was used as a target and the other as a distractor; moreover, roles of target and distractor were switched between two types of items. Thus, target and distractor had the same signal strength as a whole object; items differed only with respect to their spatial distributions of saliency strength (fluency). Furthermore, to control familiarity, the two items had the same shapes. We tested whether search efficiency differs between two conditions in order to ascertain if a difference in the saliency strength (fluency) distribution within items produces search asymmetry. As a result, search asymmetry is observed. This cannot be attributed to either of the two established factors, namely whole-signal strength effect or familiarity. Searching for a lower high saliency (or high fluency) target was a little efficient, which could suggest the operation of an unknown mechanism in visual processing.

Then, Experiment 4 was conducted to find the gradient that is essential for former three results. Searching for a lower high saliency (or high fluency) item was relatively efficient. Therefore, we tested two hypotheses by using two items. One item consisted of an upper part with high saliency strength but low fluency and a lower part with low saliency strength but high fluency, whereas the other item consisted of an upper part with low saliency strength but high fluency and a lower part with high saliency strength but low fluency. If searching for the former (lower-fluent) item among the latter (upper-fluent) items were relatively efficient, then this would

suggest that fluency gradient is an essential factor in our search asymmetry. On the other hand, if searching for the latter (lower-saliency strong) item among the former (upper-saliency strong) items were relatively efficient, then this would suggest that saliency strength gradient is essential. Results indicated that the fluency gradient is an underlying factor in the search asymmetry observed in Experiment 4.

Finally, in Experiment 5, we refuted the possibility that this type of asymmetry is simply caused by attentional habits. Consequently, these results indicate that the visual system detects fluency that is not considered as an attribute involved in a visual search. It is expected that this finding makes an important contributes to our knowledge of visual cognition.

Experiment 1

The goal in Experiment 1 was to confirm the impact of a local saliency strength gradient (or local fluency gradient) on target searches. The aim is to produce a search asymmetry based on this gradient in a situation where the possibility of either a whole-signal strength effect or a familiarity effect is eliminated. Two types of items (one for a target and the other for a distractor) were used; they consisted of two identical shapes with different luminance. It is well known that an item with high luminance has higher contrast against a black background than one with low luminance, leading to difference in the signal strength between two items (Treisman & Gormican, 1988). Thus, a part of an item with higher luminance has higher saliency strength (Treisman & Gormican, 1988) and higher fluency (Chang & Mitchell, 2009) than a part with lower luminance. However, inverting the positional relationship between parts in an item creates a distributional difference in salience strength (fluency) within an item. On the other hand, as a whole item, such a manipulation produces no difference in the whole-signal strength between a target and a distractor. In addition, the two items will not differ in overall shape; therefore, it is difficult to imagine these items will differ in familiarity. We tested whether search asymmetry occurred under these search items.

Method

Participants

The participants were 16 graduate or undergraduate students (ages 20–32 years, five females, two left-handed, all with normal or corrected-to-normal vision). The sample size for the experiment was determined on the basis of previous studies examining search asymmetry (e.g., Shen & Reingold, 2001; Wolfe, 2001).

Apparatus and stimuli

Participants were seated 56 cm from a LCD monitor (120 Hz, 23.5-in., 1920 × 1080 pixels). Stimuli were presented using MATLAB R2014a (The MathWorks, Inc.) and the Psychophysics Toolbox extensions (Brainard, 1997; Pelli, 1997; Kleiner, Brainard, & Pelli, 2007) on a black background (luminance of 0.06 cd/m²). Each search item consisted of four, eight, 12, and 16 pairs of white circles (374 cd/m², 0.82° × 0.82° in visual angle) and gray circles (7.25 cd/m², 0.82° × 0.82°), which were drawn with lines of 0.16° width and were separated by 0.14° gap. For simplicity, we defined Item A (upper part: white circle; lower part: gray circle) as an upper-luminant item and Item B (upper part: gray circle; lower part: white circle) as a lower-luminant item (see Fig. 1). Then, in Experiment 1, an upper-luminant item consisted of upper white circles and lower gray circles and a lower-luminant item consisted of upper gray circles and lower white circles. Positions where a given item appeared were determined randomly in the square region (12.2° × 12.2°), separated by at least 0.14° gaps in the region.

Procedure and design

Participants were asked to search for a target among distractors. There were two conditions (see Fig. 1). In the upper-luminant target condition, participants searched for an upper-luminant target in which the brighter white circle was above the darker gray circle but among lower-luminant distractors, which had a brighter white circle below the darker gray circle. In lower-luminant target condition, participants searched for a lower-luminant target in which the brighter white circle was below the darker gray circle among upper-luminant distractors, which had a brighter white circle above the darker gray circle. In other words, in the upper-luminant target condition, targets were upper-luminant and distractors were lower-luminant, whereas in the lower-luminant target condition, targets were lower-luminant and distractors were upper-luminant. Participants responded by pressing the “z” or “/” keys on the keyboard with their left and right index fingers, respectively. The “target-present” response was assigned to the key for their dominant hand and the “target-absent” response to the key for their nondominant hand. Participants were asked to make their responses as quickly and accurately as possible.

A 2 (target condition; upper-luminant target and lower-luminant target) × 2 (target-present and target-absent) × 4 (the number of items; four, eight, 12, and 16) within-subject design was used. The target condition was a between-block factor. The other two factors were presented in an experimental block of trials in a pseudo-random order. Four blocks, two blocks for the upper-luminant condition and two blocks for the lower-luminant target condition, were presented in a counterbalanced

Fig. 1. Experimental design used in Experiment 1. In the top box, two figures show the definition of the item. An “upper-luminant” item consisted of the upper white circle (strong/fluent) and the lower gray circle (weak/unfluent). A “lower-luminant” item consisted of the upper gray circle (weak/unfluent) and the lower white circle (strong/fluent). Figures in the bottom box show the condition design. In upper-luminant

target condition, participants searched for an “upper-luminant” target among “lower-luminant” distractors. In lower-luminant target condition, participants searched for a “lower-luminant” target among “upper-luminant” distractors. Top figures in the bottom boxes show examples of the search display when the number of items is 12

order. One experimental block consisted of 144 trials (four, the number of items $\times$ 2 target $\times$ 18 repetition). Error trials were repeated at a random point later in the block, resulting 144 correct responses in each block irrespective of the number of trials being varied depending on the number of errors made. Breaks were inserted in every 72 trials. Before starting each block of trials, participants completed a 32-trial practice.

Participants took part in a 1-hr session that started with the presentation of a set of written instructions for the task. Each trial began with the presentation of the fixation cross ($0.44^\circ \times 0.44^\circ$) for 500 ms, followed by the search display, which remained until a response made within a given period of time. If participants did not make a response within 4,000 ms, the trial was treated as an error. After the response was made (or was not made) within the deadline, the screen turned blank and remained this way for 1,000 ms; then, a fixation cross appeared for the next trial. Trials on which wrong button was pressed or the response was made in less than 150 ms were also treated as errors. In these error trials, a 530-Hz tone was given after the response.

Results

Figure 2 shows the mean correct RTs in the upper-luminant target and the lower-luminant target conditions.

RTs increased linearly with the number of items in all cases. RTs in the upper-luminant target condition were slower than those in the lower-luminant target condition. Furthermore, search slopes were steeper for the upper-luminant target condition (43.2 ms/item, $r^2 = .98$) than for the lower-luminant target condition (30.9 ms/item, $r^2 = .95$) when there was a target, and the search slopes were steeper for the upper-luminant target condition (91.0 ms/item, $r^2 = .96$) than for the lower-luminant target condition (76.6 ms/item, $r^2 = .98$) when there was no target.

Since it is known that there is a multiple-comparison problem in a multiway ANOVA (Cramer, van Ravenzwaaij, Matzke, Steingroever, Wetzels, Grasman, Waldorp, & Wagenmakers, 2016), one may argue that a two-way interaction between target condition and the number of items, which is considered as evidence of search asymmetry, is a Type I error. To avoid this problem, we tested the slope of the linear regression of the

Fig. 2 Mean correct reaction time as a function of the number of items in upper-luminant target condition and lower-luminant target condition (Experiment 1). Error bars represented the 95% confidence interval of RTs

search function in a two-way ANOVA with target condition and target presence as main factors. This analysis revealed significant main effects of the target condition, indicating that steeper slopes for the upper-luminant targets than for the lower-luminant targets, $F(1, 15) = 12.99$, $MSE = 218.76$, $p < .005$, $\eta_p^2 = .46$. It also revealed a significant effect of target presence, indicating that steeper slopes for target-absent than for target-present trials, $F(1, 15) = 80.29$, $MSE = 435.49$, $p < .005$, $\eta_p^2 = .84$, with an insignificant significant two-way interaction.

Overall, error rate was low, 5.46% (6.32% in the 36 trials) on average; this reflects a rate of 5.37% in the upper-luminant target condition and one of 5.54 % in the lower-luminant target condition. A statistical test was performed on the average error rates between two conditions, indicating no main effect of target condition and confirming there was no evidence of a negative relationship between error rate and RTs (no speed–accuracy trade-off).

Discussion

Searching for an upper-luminant (upper-strong/fluent) target among lower-luminant (lower-strong/fluent) distractors was more difficult than searching for the converse. This is consistent with the phenomenon of search asymmetry. In Experiment 1, the two known factors are not responsible for these results. Consequently, our findings indicate that when two parts with different saliency strength (fluency) are aligned vertically, the difference in local saliency strength gradient (or local fluency gradient) effect should produce search asymmetry.

Experiment 2

Experiment 1 indicated that vertical difference of local saliency strength (fluency) gradient produced search asymmetry. However, it is possible that local luminance gradient is involved in the familiarity effect. Indeed, Enns and Rensink (1990) reported that searching for a cube lightened from below among cubes lightened from above was faster than a search when these roles were reversed. They suggested that, since objects lightened from above are more common in our daily lives than those lightened from below, a difference in familiarity produced search asymmetry. It should be noted the three dimensional search items used by Enns and Rensink were completely different from the planar (2-D) items used in the present study. Nevertheless, their explanation could explain the results of Experiment 1, if the notion about local luminance difference is applied to the items in these tasks. Experiment 2 was designed to confirm the “local saliency strength gradient (or local fluency gradient) effect” using different sets of search items from Experiment 1. In Experiment 2, in order to eliminate the possibility of luminance gradient within an object, we produced a local saliency strength (fluency) difference due to vertical position of parts with different orientation. More specifically, the Gabor patches with orientations were vertically aligned to create search items, while the whole shapes of items was equivalent as in Experiment 1. It is known that tilted items have higher saliency strength than vertical items because the tilt suggests a *deviation* from *standard* vertical (Treisman & Gormican, 1988). This leads us to assume that tilted items have higher fluency than vertical items because the tilt has larger values on a quantifiable dimension than the vertical (Chang & Mitchell, 2009).

Since the contours of Gabor patches are blurred by Gaussian filtering, these items enable presentation of only differences in grating orientation while holding constant contour information. If the local saliency strength (fluency) factor holds, then the search should be more efficient when a target has a vertical grating located in the top and a (strong) tilted grating in the bottom, than when these roles are reversed.¹

¹ The saliency of a tilted segment is higher than that of a vertical one (Treisman & Gormican, 1988). This is said to be because a deviation feature (tilted feature thought to be deviated from vertical or horizontal) has higher saliency than a standard feature. As noted, not only vertical features but also horizontal features have lower saliency than do tilted features. However, we did not use a horizontal feature as a part having lower saliency in the stimulus for the following reason. Taking into consideration that a stimulus item consisting of two parts aligned vertically might have its vertical axis as the reference frame, the saliency of the part could be determined by how tilted this part was from vertical axis. In this case, the saliency of the horizontal feature will be higher than that of the tilted feature, which should contradict the assumption that tilted features have higher saliency than horizontal ones. Confounding of factors such as this may prevent us from determining the part with higher saliency. Hence, we selected a vertical part as having lower saliency and a tilted part as having higher saliency. This helped us to avoid difficulties in interpreting the experimental result.

Method

Participants

The participants were 16 graduate and undergraduate students (ages 18–23 years, three females, one left-handed, all with normal or corrected-to-normal vision). The sample size for the experiment was determined on the basis of previous studies examining search asymmetry (e.g., Shen & Reingold, 2001; Wolfe, 2001).

Apparatus and stimuli

Apparatus and stimuli were the same as in Experiment 1, except that the search items consisted of Gabor patches rather than circles. Two types of Gabor patches (three cycle/deg, $0.95^\circ \times 0.95^\circ$) separated by 0.14° gaps on the gray background (53.7 cd/m^2) were used. One was tilted 45° clockwise from vertical on its vertical axis, and the other was vertical. We hypothesized that tilted Gabor patches should have strong

salience relative to vertical Gabor patches and defined Item A (upper part: tilted patch; lower part: vertical patch) as upper-tilted item and Item B (upper part: vertical patch; lower part: tilted patch) as lower-tilted item (see Fig. 3).

Procedure and design

Procedure was the same as in Experiment 1, except that timeout was set to 6,000 ms because the search was more difficult, which was revealed in a pilot study.

Results

Figure 4 shows the mean correct RTs for the upper-tilted target condition and the lower-tilted target condition.

RTs increased linearly with the number of items for all four conditions. RTs in the upper-tilted target condition were slower than those in the lower-tilted target condition. Furthermore, the search slopes were steeper for the upper-tilted target condition (62.6 ms/item , $r^2 = .94$) than for the

Fig. 3 Experimental design used in Experiment 2. In the top box, two figures show the definition of the item. An “upper-tilted” item consisted of the upper tilted patch (strong/fluent) and the lower vertical patch (weak/unfluent). A “lower-tilted” item consisted of the upper vertical patch (weak/unfluent) and the lower tilted patch (strong/fluent). Figures in the bottom box show the condition design. In upper-tilted target

condition, participants searched for an “upper-tilted” target among “lower-tilted” distractors. In lower-tilted target condition, participants searched for a “lower-tilted” target among “upper-tilted” distractors. Top figures in the bottom boxes show examples of the search display when the number of items is 12

Fig. 4 Mean correct reaction time as a function of the number of items in upper-tilted target condition and lower-tilted target condition (Experiment 2). Error bars represented the 95% confidence interval of RTs

lower-tilted target condition (45.7 ms/item, $r^2 = .94$) when a target was present. Also search slopes were steeper for the upper-tilted target condition (118.1 ms/item, $r^2 = .98$) than for the lower-tilted target condition (95.5 ms/item, $r^2 = .98$) when there was no target.

The ANOVA of the slopes for RTs revealed significant main effects of the target condition, indicating that steeper slopes for upper-tilted than for lower-tilted, $F(1, 15) = 29.70$, $MSE = 210.13$, $p < .001$, $\eta_p^2 = .66$. Also, target presence was a significant variable; target-absent trials produced steeper slopes than target-present trials did, $F(1, 15) = 66.96$, $MSE = 662.73$, $p < .001$, $\eta_p^2 = .82$. No significant two-way interaction was observed.

Overall, error rate was low, 5.09% (6.00% in the 36 trials) on average, and 5.31% in the upper-tilted target condition and 4.80% in the lower-tilted target condition indicating that there was no possibility of speed–accuracy trade-off.

Discussion

Results of Experiment 2 replicate those of Experiment 1. The slope of the search for an upper-tilted (upper-strong/fluent) target among lower-tilted (lower-strong/fluent) distractors was steeper than the slope for the search for a lower-tilted (lower-strong/fluent) target among upper-tilted (upper-strong/fluent) distractors. Here, we again obtained a search asymmetry.

With respect to whole-signal strength, the two types of search items were equivalent. In addition, there was no concrete

difference in familiarity between these items. Consequently, the search asymmetry confirmed in this experiment is not due to the whole-signal strength effect or the familiarity effect. In addition, it is difficult to conclude that there was a familiarity difference between two items in the real world unlike in the case of Experiment 1. Rather, the result is consistent only with the local saliency strength gradient (or local fluency gradient) effect.

Experiment 3

Experiment 3 appears to confirm that a local saliency strength gradient (or local fluency gradient) affects search asymmetry using another sets of parts. It has been reported that searching for a set of Pac-Man-like figures (a circle with a quarter slice missing), arranged in an amodal shape (i.e., subjective figure) placed among other items lacking any amodal shape, is faster than searching for a target in displays in which the role of a target and a distractor was reversed (Conci, Töllner, Leszczynski, & Müller, 2011). At the same time, it is assumed that figures arranged in an amodal shape are processed more fluently than ones lacking any amodal shape. This is because amodal shapes are processed preferentially by specialized processing units in early human visual processes (von der Heydt, Peterhans, & Baumgartner, 1984). In Experiment 3, we used items involving two sets of Pac-Man-like figures, one set created an amodal shape whereas the other set formed no amodal shape; these sets were vertically arranged. In other words, in an upper-shape (upper-strong/fluent) item the upper part consisted of four Pac-Man-like figures with edges mutually aligned toward their inside direction, consequently yielding an amodal square, and the lower part consisted of four Pac-Man-like figures with edges mutually aligned toward their outside direction yielding no amodal shape. In a lower-shape (lower-strong/fluent) item, since the vertical order of two sets of figures are reversed, the upper part had no amodal shape and the lower part had an amodal shape. In other words, there was a difference in the saliency strength (fluency) between two parts due to amodal shapes, which reflects a local saliency strength gradient (or local fluency gradient) within these items. On the other hand, as in Experiments 1 and 2, there was no difference in the whole-signal strength between two items; also, it is difficult to imagine that a difference in the familiarity between two items is caused by a difference of the outlines of two parts.

Method

Participants

The participants were 16 graduate or undergraduate students (ages 19–23 years, four females, four left-handed, all with normal or corrected-to-normal vision). The sample size for

the experiment was determined on the basis of previous studies examining search asymmetry (e.g., Shen & Reingold, 2001; Wolfe, 2001).

Apparatus and stimuli

Apparatus and stimuli were the same as in Experiment 1 except that search items consisted of eight Pac-Man-like figures rather than circles. Two types of elements groups (374 cd/m², approximately 0.76° × 0.76°) separated by 0.14° gaps on the black background (7.25 cd/m²) were used. One was a Kanizsa square, induced by four inward-oriented (and edge aligned) Pac-Man-like figures, and the other was a “nonsquare” grouping, made up of four outward-oriented Pac-Man-like figures. We defined Item A (upper part: inward-oriented Pac-Man-like figures; lower part: outward-oriented Pac-Man-like figures) as upper-shape item and Item B (upper part: outward-oriented Pac-Man-like figures; lower part: inward-oriented Pac-Man-like figures) as lower-shape item (see Fig. 5).

Procedure and design

Procedure was the same as in Experiment 2.

Results

Figure 6 shows the mean correct RTs for the upper-shape target condition and the lower-shape target condition.

RTs increased linearly with the number of items in all four conditions. In the upper-shape target condition RTs were slower than RTs in the lower-shape target condition. Furthermore, the search slopes were steeper for the upper-shape target condition (61.2 ms/item, $r^2 = .97$) than for the lower-shape target condition (44.6 ms/item, $r^2 = .97$) when there was a target. However, the search slopes were not definitively steeper for the upper-shape target condition (107.6 ms/item, $r^2 = .97$) than for the lower-shape target condition (105.6 ms/item, $r^2 = .99$) when there was no target due to a great variation in a few slopes in target absent trials.

The reliability of these comparisons was established with statistical analysis. The ANOVA of the slopes for RTs revealed only a significant main effect of target presence, indicating that steeper slopes for target absent than for target present trials, $F(1, 15) = 72.54$, $MSE = 636.08$, $p < .001$, $\eta_p^2 = .83$. In addition, a significant two-way interaction emerged between target condition and target presence, $F(1, 15) = 5.20$, $MSE = 164.08$, $p < .05$, $\eta_p^2 = .26$, indicating that difference of slope in present trials was greater than that in absent trials. A post hoc Ryan test was conducted because there was two-way interaction. There was the simple main effect of target condition in target present trials, $F(1, 15) = 10.15$, $MSE = 215.85$, p

$< .01$, $\eta_p^2 = .40$, indicating that steeper slopes for upper-shapes than for the lower-shapes in present trials.

Overall, error rate was low, averaging 4.94% (5.92% in the 36 trials). Looking at error in detail, rates were 5.24% in the upper-shape target condition and 4.65% in the lower-shape target condition. There was no evidence of a negative relationship between error rate and RTs (no speed–accuracy trade-off).

Discussion

Generally, searching for an upper-shape (strong/fluent) target among lower-shape (strong/fluent) distractors was more difficult than searching for the converse, although a similar trend did not emerge in target-absent trials. Importantly, in Experiment 3, once again, the two known factors of search asymmetry are not responsible for the results. On the other hand, since the location of an amodal shape has higher saliency strength (fluency) than the location of missing shape, we found that local saliency strength gradient (or local fluency gradient) should produce search asymmetry.

Experiment 4

We obtained a novel type of search asymmetry that was not caused by the signal strength or familiarity effects. Currently, this asymmetry can be explained by the local saliency strength effect or the local fluency gradient effect. The goal of Experiment 4 was to identify the effect that is essential in the observed search asymmetry. Chang and Mitchell (2009) pointed out that (processing) fluency is an independent value of saliency strength. They showed that a normal image of an elephant (familiar object) is processed faster than an inverted image (unfamiliar object). That is, a familiar object has higher fluency than an unfamiliar object. On the other hand, Wolfe (2001) suggested that a familiar object in a visual-search task does not have as much saliency strength as an unfamiliar object.

In this experiment, two variations of an item containing two item parts were constructed using the Chinese character “舌 (normal)” and its mirrored character “舌 (reversed).” Shen and Reingold (2001) demonstrated search asymmetries when Chinese participants used “舌 (normal)” and “舌 (reversed)” visual search items, indicating that unfamiliar “舌 (reversed)” has higher saliency strength than the familiar “舌 (normal)”. Therefore, assuming differences in saliency strengths between these two item parts, there should be a local saliency strength gradient within the items in vertical part arrangements. If local saliency strength gradient is an essential factor in this type of search asymmetry, searching for a lower-unfamiliar (lower-strong) target would be more efficient than

Fig. 5 Experimental design used in Experiment 3. In the top box, two square figures defines two items. An “upper-shape” item consisted of the upper Kanizsa square, induced by four inward-oriented Pac-Man-like figures (strong/fluent) and the lower “nonsquare” grouping, made up of four outward-oriented Pac-Man-like figures (weak/unfluent). A “lower-shape” item consisted of the upper “nonsquare” grouping, made up of four outward-oriented Pac-Man-like figures (weak/unfluent) and the

lower Kanizsa square, induced by four inward-oriented Pac-Man-like figures (strong/fluent). Figures in the bottom box show the condition design. In upper-shape target condition, participants searched for an the “upper-shape” target among “lower-shape” distractors. In the lower-shape target condition, participants searched for a “lower-shape” target among “upper-shape” distractors. Top figures in the bottom boxes show examples of the each display when the number of items is eight

searching for an upper-unfamiliar target (upper-strong). On the other hand, Chang and Mitchell (2009) pointed out that the visual system cannot process an unfamiliar object as fluently as a familiar object. This suggests that the familiar “舌 (normal)” would have higher fluency than unfamiliar “舌 (reversed)”. Therefore, if the local fluency gradient is an essential factor in this type of search asymmetry, searching for an upper-unfamiliar (lower-fluent) target would be more efficient than searching for a lower-unfamiliar target (upper-fluent).

Method

Participants

The participants were 16 Japanese graduate or undergraduate students who were able to read Chinese characters (ages 19–24 years, two females, one left-handed, all with normal or

corrected-to-normal vision). The sample size for the experiment was determined on the basis of previous studies examining search asymmetry (e.g., Shen & Reingold, 2001; Wolfe, 2001).

Apparatus and stimuli

Apparatus and stimuli were the same as in Experiment 1, except that instead of circles, search items consisted of normal Chinese characters and mirrored characters. Two types of placements of a letter (374 cd/m^2 , approximately $0.76^\circ \times 0.82^\circ$), which were drawn with lines of 0.14° width and separated by 0.14° gaps on the black background (7.25 cd/m^2), were used. One was a normal (normal) (舌) and the other was a mirrored one (reversed) (舌). We defined Item A (upper part: a mirrored character; lower part: a normal character) as upper-unfamiliar item and Item B (upper part: a normal character; lower part: a mirrored character) as lower-unfamiliar item (see Fig. 7).

Fig. 6 Mean correct reaction time as a function of the number of items in upper-shape target condition and lower-shape target condition (Experiment 3). Error bars represented the 95% confidence interval of RTs

Procedure and design

Procedure was the same as in Experiment 2.

Results

Figure 8 shows the mean correct RTs for the upper-unfamiliar target condition and the lower-unfamiliar target condition.

RTs increased linearly with the number of items in all conditions. RTs in the upper-unfamiliar target condition were faster than those in the lower-unfamiliar target condition. Furthermore, search slopes were shallower for the upper-unfamiliar target condition (72.3 ms/item, $r^2 = .99$) than for the lower-unfamiliar target condition (83.0 ms/item, $r^2 = .99$) when there was a target, and the search slopes were shallower for the upper-unfamiliar target condition (153.0 ms/item, $r^2 = .99$) than for the lower-unfamiliar target condition (163.1 ms/item, $r^2 = .99$) when there was no target.

The ANOVA of the slopes for RTs revealed significant main effects of target condition, indicating shallower slopes for the upper-unfamiliar target items than for corresponding lower-unfamiliar items, $F(1, 15) = 5.03$, $MSE = 345.12$, $p < .05$, $\eta_p^2 = .25$; target presence, indicating that steeper slopes for target-absent than for target-present trials, $F(1, 15) = 101.10$, $MSE = 1022.72$, $p < .001$, $\eta_p^2 = .87$; and no significant two-way interaction.

Overall, error rate was low, averaging 5.25% (6.16% in the 36 trials). Looking at these rates in detail, they were 4.97% in

the upper-unfamiliar target condition and 5.52% in the lower-unfamiliar target condition. No evidence emerged to support a negative relationship between error rate and RTs (no speed–accuracy trade-off).

Discussion

We found a search asymmetry in Experiment 4. Searching for an upper-unfamiliar target among lower-unfamiliar distractors was easier than searching for a lower-unfamiliar target among upper-unfamiliar distractors. It is important to note that the trend of results described in Experiment 4 is inconsistent with the trend of the local saliency strength gradient's impact. If the local saliency strength gradient influences search asymmetry, as suggested in Experiments 1–3, then searching for an upper-unfamiliar (upper-strong) target among lower-unfamiliar (lower-strong) distractors in Experiment 4 would be more inefficient than searching for a lower-unfamiliar (lower-strong) target among upper-unfamiliar (upper-strong) distractors. But this was not the case. Instead, it appears that in practice, searching for an upper-unfamiliar (upper-strong) target was little easier than searching for a lower-unfamiliar (lower-strong) target. This result is not consistent with the prediction based on the local saliency strength gradient account. Rather, the results of Experiment 4 would be explained by the “local fluency gradient account” (LFG account), which states that searching for an upper-unfamiliar target (with upper-nonfluent and lower-fluent parts) is more efficient than searching for a lower-unfamiliar target (with upper-fluent and lower-unfluent parts).

Experiment 5

In Experiment 5, we tested if search asymmetry caused by LFG asymmetry is due to a biased direction of the attention movement. People always shift attention in space in downward direction because most documents are written from top to bottom. This results in people becoming accustomed to moving attention and their eyes from a higher location to a lower one (up to down). This biased habit may explain search asymmetry by LFG. If this view holds, the horizontal difference of local fluency gradient within items should produce search asymmetry because people always shift attention from left to right or from right to left, depending on their language, given that in different languages documents are almost always written in one of these directions. If these reading habits have an effect on the search asymmetry by LFG, these horizontal arrangement of parts should also show search asymmetry.

Fig. 7 The experimental design used in Experiment 4. In the top box, two figures shows the definition of the item. An “upper-unfamiliar” item consisted of the upper mirrored character (strong/unfluent) and the lower normal character (weak/fluent). A “lower-unfamiliar” item consisted of the upper normal character (weak/fluent) and the lower mirrored character (strong/unfluent). The bottom box shows the

condition design. In upper-unfamiliar target condition, participants searched for an “upper-unfamiliar” target among “lower-unfamiliar” distractors. In lower-unfamiliar target condition, participants searched for “lower-unfamiliar” target among “upper-unfamiliar” distractors. Top figures in the bottom boxes show examples of the search display when the number of items is eight

Method

Participants

The participants were 16 graduate or undergraduate students (ages 19–30 years, four females, one left-handed, all with normal or corrected-to-normal vision). The sample size for the experiment was determined on the basis of previous studies examining search asymmetry (e.g., Shen & Reingold, 2001; Wolfe, 2001).

Apparatus and stimuli

Apparatus and stimuli were the same as in Experiment 1, except that the circles were aligned horizontally. For simplicity, we defined Item A (left part: white circle; right part: gray circle) as left-luminant item and Item B (left part: gray circle; right part: white circle) as right-luminant item (see Fig. 9).

Procedure and design

The procedure was identical to Experiment 1, except that half of the participants were asked to respond “target present” by pressing the right-hand key and “target absent” by pressing the left-hand key. The other half (including one left-handed participant) asked to respond “target present” by pressing the left hand key for “target absent” and the right hand for target absent.

Results

Figure 10 shows the mean correct RTs in the left-luminant target and the right-luminant target conditions.

RTs increased linearly with the number of items in all cases. There was no difference in RTs between right and left luminant conditions. Nor were search slopes definitively steeper for the left-luminant target condition (44.2 ms/item, $r^2 = .99$) than for the right-luminant target condition (36.7 ms/item, $r^2 = .99$) when there was a target, and the search

Fig. 8 Mean correct reaction time as a function of the number of items in upper-unfamiliar target condition and lower-unfamiliar target condition (Experiment 4). Error bars represented the 95% confidence interval of RTs

slopes were not definitively steeper for the left-luminant target condition (79.6 ms/item, $r^2 = .99$) than for the right-luminant target condition (77.9 ms/item, $r^2 = .99$) when there was no target.

The ANOVA of the slopes for RTs revealed only a significant main effect of target presence, indicating that steeper slopes for target-absent than for target-present trials, $F(1, 15) = 59.69$, $MSE = 440.06$, $p < .001$, $\eta_p^2 = .80$. There was no significant two-way interaction.

Overall, the error rate was low, averaging 4.90% (5.56% in the 36 trials). Looking at errors in detail, rates were 5.17% in the left-luminant target condition and 4.63% in the right-unfamiliar target condition. Subsequently, statistical tests were performed on the average error rates between two conditions, indicating that there was no main effect of target condition.

Discussion

There was no sign of search asymmetry in Experiment 5. The design of this experiment paralleled that of Experiment 1 with the exception that parts of an item were horizontally arranged. As noted earlier, participants are accustomed to moving attention from left to right as well as from top to bottom based on reading and searching habits. Therefore, if the directional habit of attention movement causes search asymmetry by LFG, then there should be an indication of search asymmetry in this experiment. However, in fact, no asymmetry appeared with horizontal pairs. Thus, we conclude that this attentional habit is not a cause of search asymmetry by LFG.

General discussion

The evidence for a novel search asymmetry

A series of series experiments (in Experiments 1–4) all showed asymmetries in patterns of search reaction times. The search asymmetry we found in this study cannot be explained by two previously known factors of search asymmetry, such as whole-signal strength and familiarity. First, a whole-signal strength effect refers to a search asymmetry caused by a difference in the relative signal strength of a target and a distractor. Presumably, this occurs because attention is preferentially guided to the item with more features (Wolfe, 1994; Wolfe, Cave, & Francel, 1989). However, this explanation is not consistent with results in the present experiments, in which a target and a distractor shared two common parts.

Next, the familiarity effect is a trend in which the search for a target with low familiarity among distractors with high familiarity is faster than when these roles are reversed (Malinowski & Hübner, 2001; Shen & Reingold, 2001; Wang et al. 1994; Wolfe, 2001). Although familiarity of a visual object is affected by several factors, shape is a most important one. In our study, however, we selected parts with the same outline shape for a target and for a distractor in Experiments 1 and 2, and with very similar outline shapes in Experiments 3 and 4, enabling us to equate the global shapes of these two items. Enns and Rensink (1990) have argued that a vertical luminance gradient within items can induce search asymmetry based on a familiarity difference. However, none of the gradients in Experiments 2, 3, and 4 were luminance gradients, suggesting that luminance-based familiarity does not explain all results reported in this study.

Rauschenberger and Yantis (2006) proposed that the difference in *redundancy* of search items produces search asymmetry. More specifically, they argued that difference in redundancy of distractors that comprises the majority on a search display could be a factor of search asymmetry. They provided a definition of redundancy based on Garner (1962, 1974) as follows: “Garner made the concept of redundancy applicable to individual stimuli by proposing that every stimulus is treated by observers as originating from an implicit set of alternative stimuli” (Rauschenberger & Yantis, 2006, p. 123). For example, consider the case where a single numeric character or letter of an alphabet is selected as a search item. Since an implicit set of numeric characters is 10 (i.e., 0–9) and that of alphabets is 26 (i.e., A–Z), and the set of numeric characters is smaller than that of alphabets, a numeric character (e.g. “5”) has higher redundancy than a letter (e.g. “E”). Searching for a numeric character among alphabets can be more difficult than searching for an alphabetic letter among numeric characters because letters that are processed often as distractors in the former search condition have lower redundancy and take a longer time to be processed than do numeric characters that

Fig. 9 Experimental design used in Experiment 5. In the top box, two figures shows the definition of the item. A “left-luminant” item consisted of the left white circle (fluent) and the right gray circle (unfluent). A “right-luminant” item consisted of the left gray circle (unfluent) and the right white circle (fluent). Figures in the bottom box show the

condition design. In left-luminant target condition, participants searched for a “left-luminant” target among “right-luminant” distractors. In right-luminant target condition, participants searched for a “right-luminant” target among “left-luminant” distractors. Top figures in the bottom boxes show examples of the search display when the number of items is 12

are processed more often in the latter condition. Although redundancy can be a factor of search asymmetry, it is difficult to imagine that there is a redundancy difference between two types of items used in our experiments.

How does search asymmetry occur?

The present results reveal that LFG within items produces search asymmetry. In particular, searching for a target with an upper-unfluent part and a lower-fluent part was more efficient than searching for a target with an upper-fluent part and a lower-unfluent part. Given our LFG account, it is worth discussing how this account affects search efficiency. Here, we consider the possibility that search asymmetry by LFG is explained by the familiarity factor of search asymmetry. In previous sections, we considered that an upper-fluent item is as familiar as a lower-fluent item, because one item does not “look” more familiar than another item. However, we can imagine that one is more familiar than the other even though we are not aware of the difference of familiarity. For instance,

in communicating other persons, faces contain a great deal of information. Therefore, visual system may process faces as a fluent part. Since a face is located in the upper part of a body, the visual system sets higher priority for the upper part of the whole human body. Additionally, in terms of the face itself, eyes may be a relevant and fluent feature and are located in the relatively upper part of a face. In these cases, our visual system may have overlearned how to process upper-fluent parts of objects. Considering such issues, upper-fluent items can be processed in a similar way as familiar objects.

Conclusion: Detection mechanism of local fluency gradient

We found a novel search asymmetry that cannot be explained as a whole-signal strength effect or a familiarity effect. Instead, a new hypothesis, summarized as the LFG effect, determines search asymmetry in a task consisting of two types of search items that are different only in their relationship between two common parts that have different fluency. This

Fig. 10 Mean correct reaction time as a function of the number of items in left-luminant target condition and right-luminant target condition (Experiment 5). Error bars represented the 95% confidence interval of RTs

leads us to accept that the visual system detects LFG. Importantly, LFG is a common feature across a wider range of visual objects, created by rather basic visual properties such as luminance or orientation or by configurational properties such as contours or characters. To the best of our knowledge, no study has reported LFG as visual feature. Logan (1994) suggested that spatial attention is the only factor that enables participants to understand the positional relationship of aligned two parts. However, our study shows that LFG is possibly computed without involving visual attention. Further research is required to reveal the LFG detection mechanism involved in this type of search asymmetry and provide relevant insights into visual cognition studies.

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