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Attentional guidance varies with display density

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ABSTRACT

The aim of the present study was to investigate how display density affects attentional guidance in heterogeneous search displays. In Experiment 1 we presented observers with heterogeneous sparse and dense search displays which were adaptively changed over the course of the experiment using genetic algorithms. We generated random displays, and based upon fastest search times, the displays that allowed most efficient search were selected to generate new displays for the next generations, thus revealing which properties facilitated or inhibited target search across display densities. The results showed that the prevalence of distractors sharing the target color was substantially reduced over generations in sparse displays. Dense displays also evolved to contain less distractors sharing the target color but only when the orientation of the distractors resembled the target orientation. More importantly, spatial analyses revealed that changes across generations occurred across all areas in sparse displays but were confined to occur around the target location only in dense displays. In Experiment 2, in which we used a factorial design, we showed that the presence of potentially interfering distractors in the target area affected search in dense displays but not in sparse displays. Together the results suggest that the role of salience-driven attentional guidance is larger in dense than sparse displays even in the absence of display homogeneity.

1. Introduction

It has been known for a long time that when people search for a specific target in their visual surroundings, they cannot process all visual information simultaneously. Rather, they need to sequentially deploy visual attention to various locations in the visual field in order to identify and recognize the target. The requirement of attentional processing in visual search poses a serious challenge to our visual system, for it is time-consuming and might potentially lead to highly inefficient search. Yet, attention is usually not randomly allocated but can be guided by a large variety of properties in the visual environment (Wolfe & Horowitz, 2017). Typically a distinction is made between bottom-up salience-driven guidance and top-down feature-driven guidance (see Awh, Belopolsky, & Theeuwes, 2012; Wolfe & Horowitz, 2017 for other types of guidance).

In bottom-up salience-driven guidance, visual attention is biased to prioritize those parts of the visual environment that are distinct relative to their surroundings. Thus attention may be captured by a single horizontal line among multiple vertical lines or by a red circle among green circles. The more distinct or salient a specific location is, the more likely it is that it will attract attention (Itti & Koch, 2000, 2001; Itti, Koch, & Niebur, 1998; Theeuwes, 1991; Yantis & Jonides, 1990). Salience-driven guidance is data-driven implying that its effects on visual selection are fully determined by the physical properties of stimuli in the environment and thus occur independently from the goals of an observer.

In top-down feature-driven guidance, attention is biased to specific target features (Bacon & Egeth, 1994; Folk, Remington, & Johnston, 1992; Green & Anderson, 1956; Williams, 1967). That is, task-relevant features can be voluntarily used to guide attention to those objects that possess those features (Wolfe & Horowitz, 2017; Wolfe, 1994; Wolfe, Cave, & Franzel, 1989). Feature-driven guidance is ultimately governed by the internal goals of observers. For example, observers may selectively attend only to those objects that share the target color and ignore all differently colored objects (e.g., Kaptein, Theeuwes, & Vanderheijden, 1995) or selectively search for one letter shape and exclude other letter shapes, irrespective of the color (Egeth, Virzi, & Garbart, 1984). Attentional feature guidance has been demonstrated for many different properties such as color, motion, orientation, and size (e.g., Irons & Leber, 2016; Wolfe & Horowitz, 2004, 2017) and evidence

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suggests that people may even selectively search for multiple features simultaneously (e.g., Adamo, Wozny, Pratt, & Ferber, 2010; Nordfang & Wolfe, 2014). Moreover, this type of guidance is flexible, such that the attentional settings can be adaptively changed in order to optimize search in a specific context (e.g., Becker, 2010; Becker, Folk, & Remington, 2013; Bravo & Farid, 2016).

Whether target search is based on salience-driven or feature-driven control has been demonstrated to depend on the similarity between target and distractors and on the similarity between the distractors (Duncan & Humphreys, 1989; Liesefeld, Moran, Usher, Muller, & Zehetleitner, 2016; Wolfe & Horowitz, 2017). More specifically, when a search display consists of a single distinct feature singleton target among multiple homogenous other items, search efficiency is typically high and independent of the number of items in the display suggesting that in such displays salience-driven guidance prevails and that attention is involuntarily captured by the singleton target that pops out. Conversely, when a search display does not contain one single item that stands out but consists of multiple heterogeneous items, search efficiency typically decreases with the number of items in the display. Presumably, salience can no longer reliably guide attention to the target location and search tends to become feature-based (Wolfe et al., 1989; Wolfe, 1994, 2001).

Recently, Rangelov, Muller, and Zehetleitner (2017) proposed that the extent to which search is salience-based or feature-based does not depend on the presence of a pop-out target but merely depends on display density. Using search displays consisting of one distinct feature singleton target and multiple homogenous distractors, Rangelov et al. (2017) explicitly tested whether search for a target proceeds in a similar fashion across different display densities. In modelling the response time distributions, they found that observed performance differences across different display densities could only be accounted for by assuming concomitant changes in target salience. In fact, their results showed that a feature singleton target failed to pop out in the majority of trials in sparse displays whereas this was not the case in dense displays. These findings correspond to previous results showing that a target becomes more salient when the local contrast at its location is enhanced through increased display density (Nothdurft, 2000; Sagi & Julesz, 1985) and show that local differences in feature contrast across different display densities change the availability of salience information and consequently the relative importance of salience-driven guidance in search (see also: Meinecke & Donk, 2002; Schubo, Schroger, & Meinecke, 2004; Sobel, Pickard, & Acklin, 2009; Todd & Kramer, 1994).

If the reliance on salience-driven guidance varies with display density in homogeneous displays then the question arises whether guidance in heterogeneous displays is subject to a similar change. Search in heterogeneous displays is generally less efficient than in homogeneous displays and attentional guidance is mostly inferred to be feature-based (Wolfe & Horowitz, 2017). Yet, studies investigating visual search in heterogeneous displays have mostly used relatively sparse displays (Bacon & Egeth, 1994; Folk et al., 1992; Kaptein et al., 1995). However, there are various reports suggesting a role of salience-driven guidance in real-world images which are typically dense and highly heterogeneous (N. C. Anderson, Ort, Kruijne, Meeter, & Donk, 2015; Parkhurst, Law, & Niebur, 2002). Moreover, it is well known that the ability to identify individual features deteriorates when display density increases (Bouma, 1970; Pelli, Palomares, & Majaj, 2004; but see Van der Burg, Olivers, & Cass, 2017; Wallis, Tobias, Bethge, & Wichmann, 2017). These identification difficulties are often explained in terms of visual crowding and are thought to reflect processes of feature averaging (Parkes, Lund, Angelucci, Solomon, & Morgan, 2001), or source confusion (Ester, Klee, & Awh, 2014; Krumhansl & Thomas, 1977; Krumhansl, 1977; Strasburger & Malania, 2013; Strasburger, 2005). Accordingly, if display density increases so does visual crowding which may subsequently limit the possibility to use specific features in the guidance of attention. Van den Berg, Roerdink, and Cornelissen (2007) investigated how the identification thresholds of targets specified by orientation, size, color, and hue varied as function of crowding. Apart from their finding that identification thresholds generally increased with crowding, they also showed that these effects were much stronger for orientation and size than for color and hue, suggesting that the identifiability of different features can be differently affected by display density. Increasing display density may therefore not only limit feature-based guidance but may also fundamentally alter the specific features used in the guidance of attention.

The present study aims to investigate how display density changes attentional guidance in complex heterogeneous search displays. To examine how display density affects attentional control, we presented observers with heterogeneous search displays which were adaptively changed over the course of the experiment using a genetic algorithm (see: Kong, Alais, & Van der Burg, 2016a; Van der Burg, Cass, Theeuwes, & Alais, 2015). A genetic algorithm (GA) is an optimization technique for solving complex problems by mimicking natural selection (Holland, 1975). Even though a GA is a common technique in computer science, it has only recently been applied to investigate visual search behavior in complex heterogeneous displays (Kong et al., 2016a; Kong, Alais, & Van der Burg, 2016b; Van der Burg et al., 2015, 2017). The application of a GA in a visual search context efficiently allows the collection of information about the stimulus properties that matter in target search. Importantly, a GA does not only reveal which features are used in the guidance of attention but also allows to investigate which changes occur in the immediate target surroundings thus providing an indication of the relevance of local feature contrast in target search (Van der Burg et al., 2015).

In the present study we used the GA method while manipulating display density across two conditions: low density and high density (with 24 or 84 distractors, respectively). In both conditions, participants started with randomly assigned display configurations consisting of multiple line segments with various colors (red, green, and blue) and orientations (horizontal, vertical, and 10° from horizontal). None of these distractors were red and horizontally oriented as this was the target object. The target was always present, and contained a gap which was positioned slightly offset towards the left or right. Participants made a speeded response to the location of this gap. Fig. 1 illustrates an example of a low-density and a high-density display. For the first generation, we generated 12 random displays by assigning a random color and orientation to each distractor. For the subsequent generations the distractor identities varied over generations depending on the participant's performance. After each block of trials (a generation), the displays with the shortest reaction times (RTs) were selected (survival of the fittest principle) and used to create new 'evolved' displays for the next generation (similar to the method of Van der Burg et al. (2015), see also Van der Burg et al. (2017)). Subsequently, participants performed the search task on the new evolved displays, and the evolutionary procedure was repeated for 6 generations for each condition twice.

In principle, we expect search to improve over generations, as the most detrimental distractors will disappear over generations given the fact that we apply a survival of the fittest principle. By investigating the evolution process of the displays across generations, we aim to determine which distractor features contribute to more efficient or less efficient search over generations in low-density and high-density displays. If search is initially salience-driven, selection should be biased to those parts of the display that are locally distinct (Itti & Koch, 2000, 2001). Accordingly, salience-driven search should lead to local changes that increase the conspicuity of the target. If search is initially feature driven, changes over generations should occur throughout the display for feature-driven selection is governed by the internal goals of the observer which operate across the entire display.

If display density affects the availability of salience information, and consequently the possibility to rely on salience in attentional guidance, it is predicted that the local prevalence of individual features around the target position, varies between low-density and high-density displays. Display density may not only affect the availability of salience

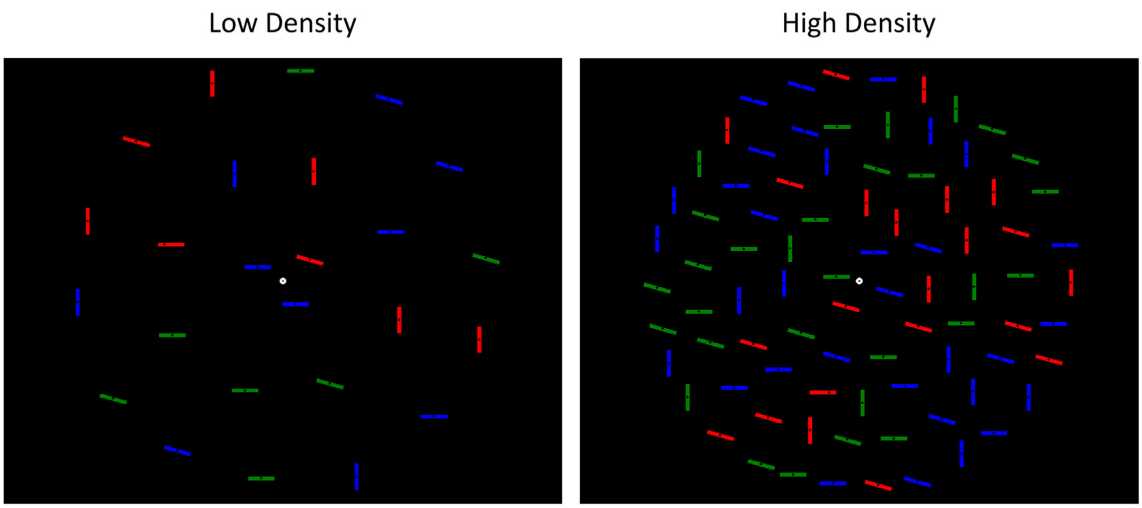

Fig. 1. Sample displays for the low- and high-density display conditions used in Experiment 1. Participants searched for the red horizontal line. The target contained a gap which was positioned slightly offset towards the left or right, and participants made a speeded response to the location of the gap. Here, the gap location is left and right in the low- and high-density display, respectively.

information but may also alter the features used in top-down guidance. If feature-based guidance varies across display density, it is predicted that the overall prevalence of individual features across the entire display differs between low-density and high-density displays.

2. Experiment 1

2.1. Methods

2.1.1. Participants

Twelve participants (mean age = 24.8, ranging from 19 to 33 years, 6 females) took part in the experiment. Participants were naive as to the purpose of the experiment and received course credits or money (€10 per hour) for their participation. They had normal or corrected-to-normal vision. All participants provided written consent. The experiment was approved by the local ethics committee of the Vrije Universiteit Amsterdam and conducted in accordance with the Declaration of Helsinki.

2.1.2. Task and stimuli

Participants were seated in a sound-isolated and dimly lit cubicle with their heads stabilized by a chin rest at a distance of approximately 70 cm from the 22-inch monitor (Samsung SyncMaster; refresh rate 100 Hz, resolution 1024 × 768). Eye height corresponded to the middle of the screen. The experiment was programmed using OpenSesame software (Mathot, Schreij, & Theeuwes, 2012) and responses were given using a regular QWERTY keyboard.

Stimulus displays always consisted of a central white fixation dot (0.45° of visual angle, CIE x-, y-, z-chromaticity coordinates of 94.4, 102.7, 116.7, with a luminance of 103 cd/m2) and multiple red (CIE x-, y-, z- chromaticity coordinates of 43.6, 25.1, 1.5, with a luminance of 25 cd/m2), green (CIE x-, y-, z- chromaticity coordinates of 4.6, 10.1, 2.1, with a luminance of 10 cd/m2), and blue (CIE x-, y-, z- chromaticity coordinates of 20.4, 12.7, 102.1, with a luminance of 13 cd/m2) line segments varying in orientation (horizontal: 0°, tilted: 10°, and vertical: 90°).

The background color was black ($< 0.5\ \mathrm{cd/m^2}$) and kept constant during the course of the experiment. The target was defined by the unique combination of red and horizontal, whereas the other line segments, the distractors, were equally likely composed of either one of the other eight possible combinations of color and orientation. Every line segment subtended 0.25° x 1.47° of visual angle and contained a small circular gap (0.12° of visual angle) which was positioned slightly offset towards the left or right in the target and positioned in the middle in the distractors. Participants had the task to search for the target and to indicate the position of the gap by pressing the z- or m-key when the gap was presented at the target's left or right side, respectively. On half of the trials the gap was at the target's left side, and on the other half at the target's right side.

There were two density conditions: low density and high density (see Fig. 1). In the low-density condition stimulus displays consisted of 25 line segments presented at the circumferences of three imaginary circles (with a radius of 1.6°, 6.2°, and 10.8° containing 3, 8, and 14 line segments, respectively) centered around the fixation dot. In the high-density condition stimulus displays consisted of 85 lines presented at the circumferences of five imaginary circles (with a radius of 1.6°, 3.8°, 6.2°, 8.5°, and 10.8° containing 4, 11, 17, 23, and 30 line segments, respectively) centered around the fixation dot. The individual line segments were presented at equally spaced locations on each of the imaginary circles such that the approximate center-to-center distance between line segments was on average 4.8° of visual angle in the low-density condition and 2.4° in the high-density condition. In both conditions, each line was centered at its location with a random jitter between −0.37° and 0.37° in horizontal and vertical direction. Regardless the density condition, the target eccentricity was fixed (6.2°) and its location was never jittered. Participants were aware that the target eccentricity was fixed.

2.1.3. Design and procedure

Each trial began with the presentation of a fixation dot for 500 ms followed by the search display which was presented until the participant gave a response. Participants saw a red or white fixation dot for 500 ms when the response was incorrect, or correct respectively, before the next trial was initiated. Participants were instructed to fixate the central fixation dot at the start of each trial and respond as fast and accurately as possible.

Each participant performed 26 blocks, consisting of 72 trials each. The first two blocks were practice blocks, one corresponding to the low-density and one to the high-density condition. For each density condition two series of six blocks (generations) were presented. Each sequence started with totally new and randomly chosen stimulus displays for each participant. Over the course of the experiment, the blocks corresponding to the two density conditions were presented in alternating order and counterbalanced across participants. Participants could take a break after each block of trials. The experimental session took approximately 100 minutes.

2.1.4. Genetic algorithm

For the first generation (i.e., the first experimental block of each sequence) of each density condition, twelve unique displays were randomly generated by assigning a random orientation and color to each distractor in the display with the constraint that none of the distractors was red and horizontal (the target). Together these twelve displays compromised the first generation. Within a block, each display was repeated six times. The 72 displays (12 displays × 6 repetitions) were presented in a random order. The spatial configuration in each display remained the same across repetitions, but displays were rotated with a randomly determined angle around fixation (chosen from 20 possible rotations, equally distributed over 360°, i.e., 18, 36, 54°, etc.) to maintain a difficult search task (see also Van der Burg et al., 2015). That is, the retinotopic location of each element in the display was changed, but its identity and its position relative to the other elements in the display were preserved across rotations. Accordingly, the rotation had no impact on the individual distractor orientations, such that, for example, a horizontal distractor remained horizontal regardless of the display rotation.

After each block (generation), for each of the twelve unique displays the correct median reaction time (RT) was calculated and following a "survival of the fittest" principle, the four displays with the fastest correct median RT, the "parents", were selected. The parents were used to create 12 new unique displays, the "children", for the next block (i.e., the subsequent generation) using a crossover and mutation procedure similar as in Van der Burg et al. (2017).

The four best displays were used to generate 12 evolved displays using a uniform crossover procedure with a mixing ratio of 50%. With two parents we can create two children. For one child, for each distractor location, a distractor was chosen from either parent with equal probability (i.e., the mixing ratio). For the other child, a distractor was chosen from the parent that was not selected. As a result, both children inherit 50% of both parents. To create the 12 children from the parents, each of the parents mated with every other parent, resulting in a total of six crossover sessions. Finally, each distractor in the new evolved displays had a 4% probability to randomly mutate to one of the eight distractor combinations.

2.2. Results

2.2.1. Mean error rate

Practice trials were discarded from further analyses. The results were collapsed over both series. The mean error rate was 3.1%. An ANOVA on mean error rate with generation and density condition as within-subject variables yielded no significant effects (all p's $> .423$).

2.2.2. Mean correct RT

Fig. 2 illustrates the mean correct RT as a function of generation for each density condition collapsed over both series.

In the following analyses, in those cases in which the assumption of Sphericity was violated ($p < .05$), degrees of freedom were corrected using Greenhouse-Geisser estimates of Sphericity. A repeated-measures ANOVA on the individual mean correct RTs with Density (low and high) and Generation (1–6) as within-subject variables was conducted. The ANOVA yielded a significant Density effect, $F(1, 11) = 63.68$, $p < .001$, $\eta_p^2 = 0.853$, as search was slower for the high-density condition (1242 ms) than for the low-density condition (736 ms). The ANOVA yielded a significant Generation effect, $F(2.49, 27.44) = 74.88$, $p < .001$, $\eta_p^2 = 0.872$, as search improved over generations. The two-way interaction was also significant, $F(2.75, 30.29) = 25.77$, $p < .001$, $\eta_p^2 = 0.701$, showing that search benefits over generations were larger in the high-density than in the low-density condition.

2.2.3. Changes in distractor prevalence across generations

To investigate which distractors contributed to the observed increase in search efficiency across generations, we calculated the distractor proportions in the display for each level of Distractor type, Generation, and Display density separately per participant. Even though each participant only searched through six successive generations of displays, the following analyses are based on seven generations. The addition of a seventh generation was realized by evolving the displays a final time as we had a measure of fitness for each of the displays in Generation 6.

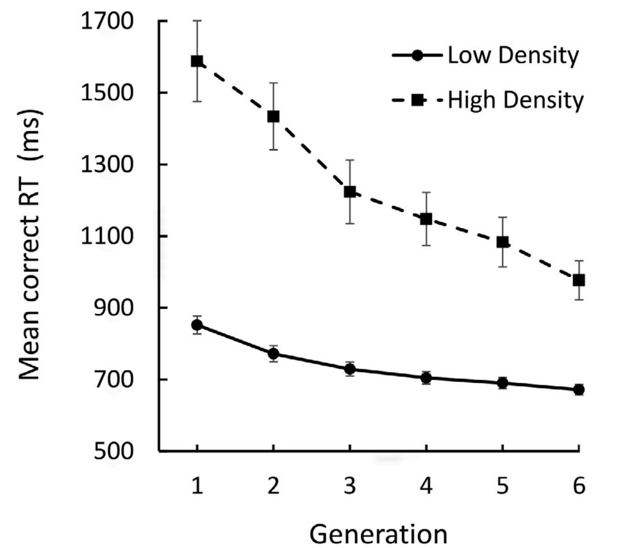

Fig. 2. Mean correct RT, separately for each generation in the low-density and high-density condition collapsed over both series. Error bars reflect the standard error of the mean.

We fitted a power function (see Eq. (1)) to the individual data in order to examine whether distractor proportions increased or decreased over generations (see Van der Burg et al., 2015 for a similar procedure):

$$f(x) = ax^b \quad [1]$$

Here, parameter a represents the distractor proportion in the first generation and parameter b the rate of change in the distractor proportion over the successive generations. A positive value of b signifies an increase in distractor proportions over successive generations, whereas a negative value reflects a decrease in distractor proportions over successive generations. The variable x indicates the generation number and ranges from 1 to 7. Fig. 3 shows the mean distractor proportions as a function of generation separately for the low- and high-density condition and the best fitting power functions. Fig. 4 shows the mean values of the rate parameter b as a function of distractor type and display density.

A repeated-measures ANOVA on the individual estimates of the rate (b) with Distractor type (1–8) and Density (low and high) as within subject variables revealed a significant Distractor-type effect, $F(7, 77) = 20.75$, $p < .001$, $\eta_p^2 = 0.654$, and a significant Density effect, $F(1,11) = 36.89$, $p < .001$, $\eta_p^2 = 0.770$. The interaction between Density and Distractor type was also significant, $F(7, 77) = 6.28$, $p < .001$, $\eta_p^2 = 0.363$. To further investigate the rates of change over successive generations, we performed multiple t-tests in which we tested each b value against zero (using a Bonferroni-adjusted α of 0.003). The results revealed that there was a significant decrease in the number of red vertical ($t(11) = 4.99$, $p < .001$) and red tilted distractors ($t(11) = 5.92$, $p < .001$) in the low-density condition whereas there was only a significant decrease in the number of red tilted distractors ($t(11) = 4.30$, $p < .001$) in the high-density condition (see Fig. 4). The rates of change corresponding to the other combinations of Distractor type and Display density did not differ significantly from zero (all p's $> .014$).[1] The mean estimated value of parameter a across all distractor types and both display densities was 0.127, which reflects the initial proportion of each distractor type in the first generation.

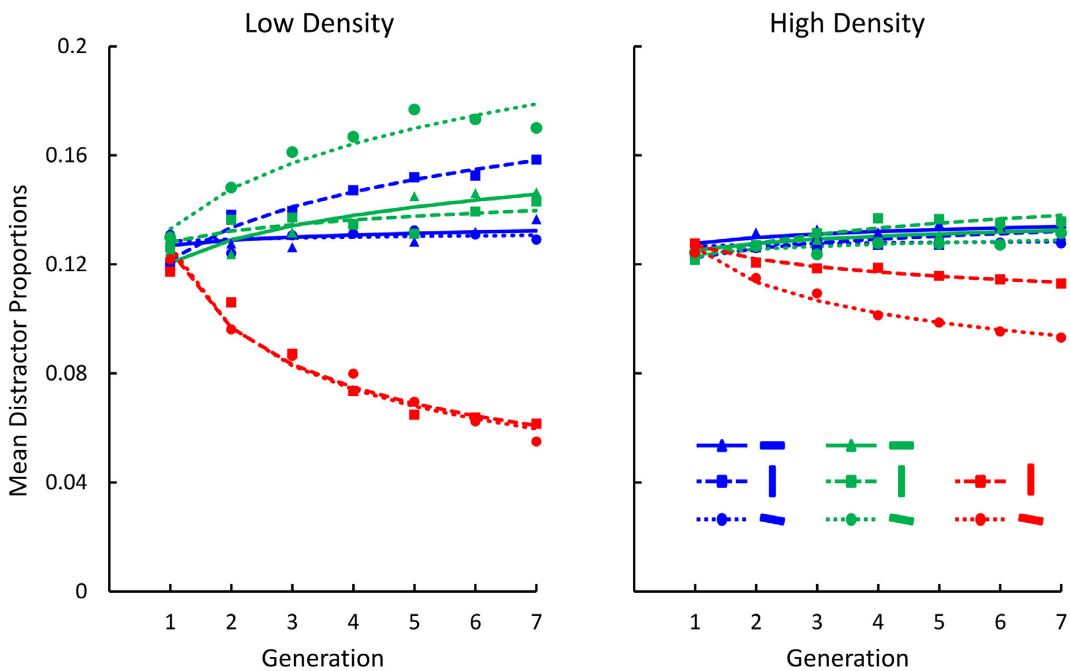

Fig. 3. Results of Experiment 1. Mean distractor proportions in the display separately for each generation and each distractor type in the low-density and high-density condition. The continuous lines represent the best fitting power functions (Eq. (1)).

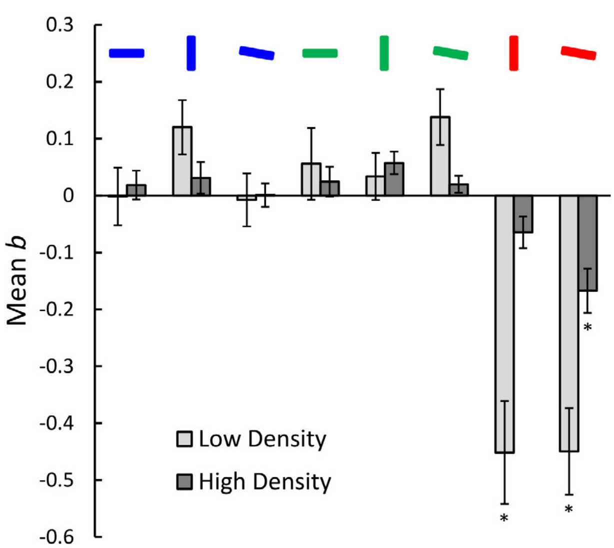

Fig. 4. Mean values of the parameter *b* separately for each distractor type in the low- and high-density condition. Here, a positive *b*-value indicates an increase in distractor proportions over successive generations whereas a negative *b*-value corresponds to a decrease. Error bars reflect the standard error of the mean. Asterisks (*) indicate significant differences from zero (Bonferroni-adjusted $\alpha = 0.003$).

[1] Even though the rates of change corresponding to the blue and green distractors did not differ significantly from zero when using a Bonferroni-adjusted α of 0.003, the decrease in prevalence of the red distractors tended to be primarily compensated by an increase in the prevalence of the blue vertical distractors ($t(11) = 2.52$, $p = .028$) and the green tilted distractors ($t(11) = 2.81$, $p = .017$) in the low-density condition and the green vertical distractors ($t(11) = 2.90$, $p = .014$) in the high-density condition. This suggests that display density did not only differentially affect the prevalence of the red distractors but also the prevalence of the other distractors.

2.2.3.1. Spatial changes in the mean distractor proportions from generation 1 to 7. In order to investigate whether the observed changes in the prevalence of the different distractor types were evenly distributed across the display or locally restricted to the target region only, a spatial analysis was performed in which we examined the mean distractor proportions across all angular directions from fixation separately for the first and seventh generation in the low-density and high-density condition. The spatial analysis was performed by rotating a 90 degree pie slice per degree and by depicting the distractor proportions within the slice at each rotation position separately for each distractor type, density condition (low-density and high-density condition), and generation (Generation 1 and 7). Differences in distractor proportions between Generation 1 and 7 were tested by paired-samples t-tests, and p-values were FDR corrected (see Benjamini & Hochberg, 1995). The results for the low- and high-density condition are depicted in Fig. 5A and B, respectively.

The results obtained in the spatial analyses demonstrate that in the low-density condition, changes in distractor proportions occur throughout the entire display whereas in the high-density condition, changes are confined to the target region only. That is, even though the prevalence of red tilted distractors was reduced from Generation 1 to 7 in both, the low-density and the high-density condition, the prevalence of the red tilted distractors were reduced across the entire display in the low-density condition whereas this reduction was confined to the target region only in the high-density condition.

2.3. Discussion

The results of Experiment 1 show that in the low-density condition the prevalence of both the red tilted and the red vertical distractors was substantially reduced from Generation 1 to Generation 7. In the high-density condition, only the prevalence of the red tilted distractors was reduced. Importantly, whereas changes across generations occurred throughout the entire display in the low-density condition, changes in the high-density condition were confined to occur in the target area only. This suggests that attentional guidance differs when searching through a low-density or a high-density display. Guidance in a low-density display appears to be primarily driven by color: the prevalence

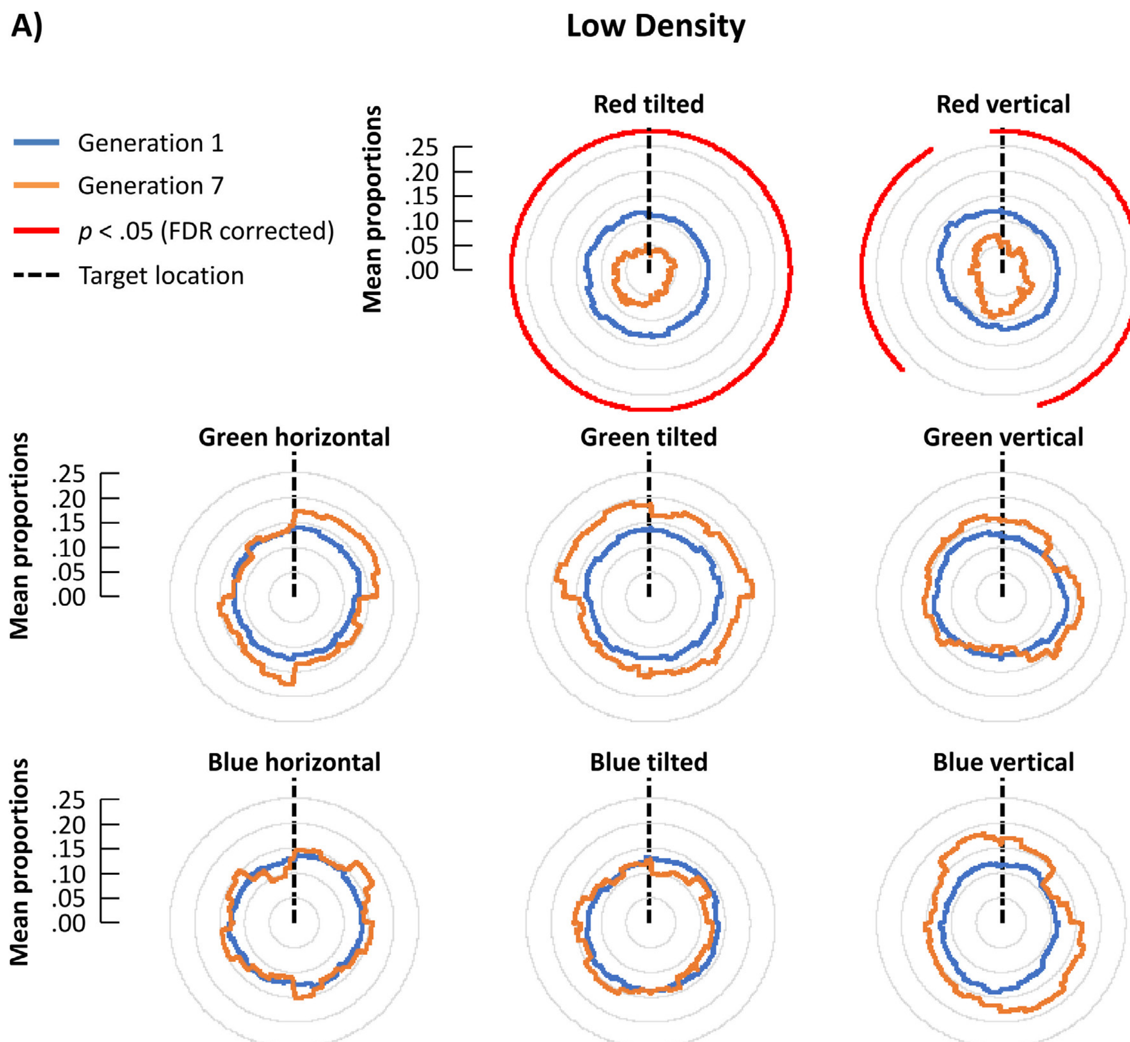

Fig. 5. Mean distractor proportions across all angular directions from fixation, separately for Generation 1 and 7 in the low-density and high-density condition (Panel A and B, respectively). The black dotted line indicates the direction of the target position.

of red distractors was reduced over generations, irrespective of whether these distractors were tilted or vertically oriented and irrespective of whether these distractors were presented in the vicinity of the target or not. Guidance in a high-density display takes another form: high-density search seems to rely on the properties of the distractors in the direct vicinity of the target only. This suggests that even though the presented displays were highly heterogeneous, guidance in such displays were at least partly driven by salience.

The present results are in line with those of Rangelov et al. (2017) who demonstrated that the effect of salience on visual selection co-varies with display density. In their study it was shown that even though a feature singleton tended to be the first item inspected in high-density displays, it failed to pop out in low-density displays. Although we used heterogeneous displays, the present findings are very similar. While low-density search produces changes across the entire display, high-density search leads to changes in the target area only. This suggests that attentional guidance differs between low-density and high-density displays. Whereas search through a low-density display does not depend on the presence of local feature discontinuities, high-density search does.

Despite the difference observed between the low-density and the high-density condition of Experiment 1, it is important to note that these findings were generated through the application of a GA and represent as such exploratory rather than conclusive data. In order to test whether low-density and high-density search differ in their reliance on local feature contrast, we performed a second experiment in which we factorially manipulated the presence of interfering distractors in the target quadrant in both density conditions.

3. Experiment 2

The aim of Experiment 2 was to test whether the presence of potentially interfering distractors in the target quadrant is more disruptive to search in a high-density display as compared to a low-density display. The task and displays used in Experiment 2 were similar to those used in Experiment 1 except that in Experiment 2 we systematically manipulated the presence of red tilted distractors around the target position in a factorial design. In Experiment 2, the displays were divided in four quadrants. In three quadrants we had the same eight distractor types as in Experiment 1. In the other quadrant (the critical quadrant) we had the same distractor types, except that the red tilted distractor was never presented, so that we had only seven distractor types in total. The target was equally likely presented in either one of the quadrants with the result that on average in 25% of the trials, the target was presented in the critical quadrant, and in 75% in one of the other quadrants. We expect a quadrant x density interaction, indicating that search is better when the target is presented in the critical quadrant than the other quadrants, but only for the high-density condition.

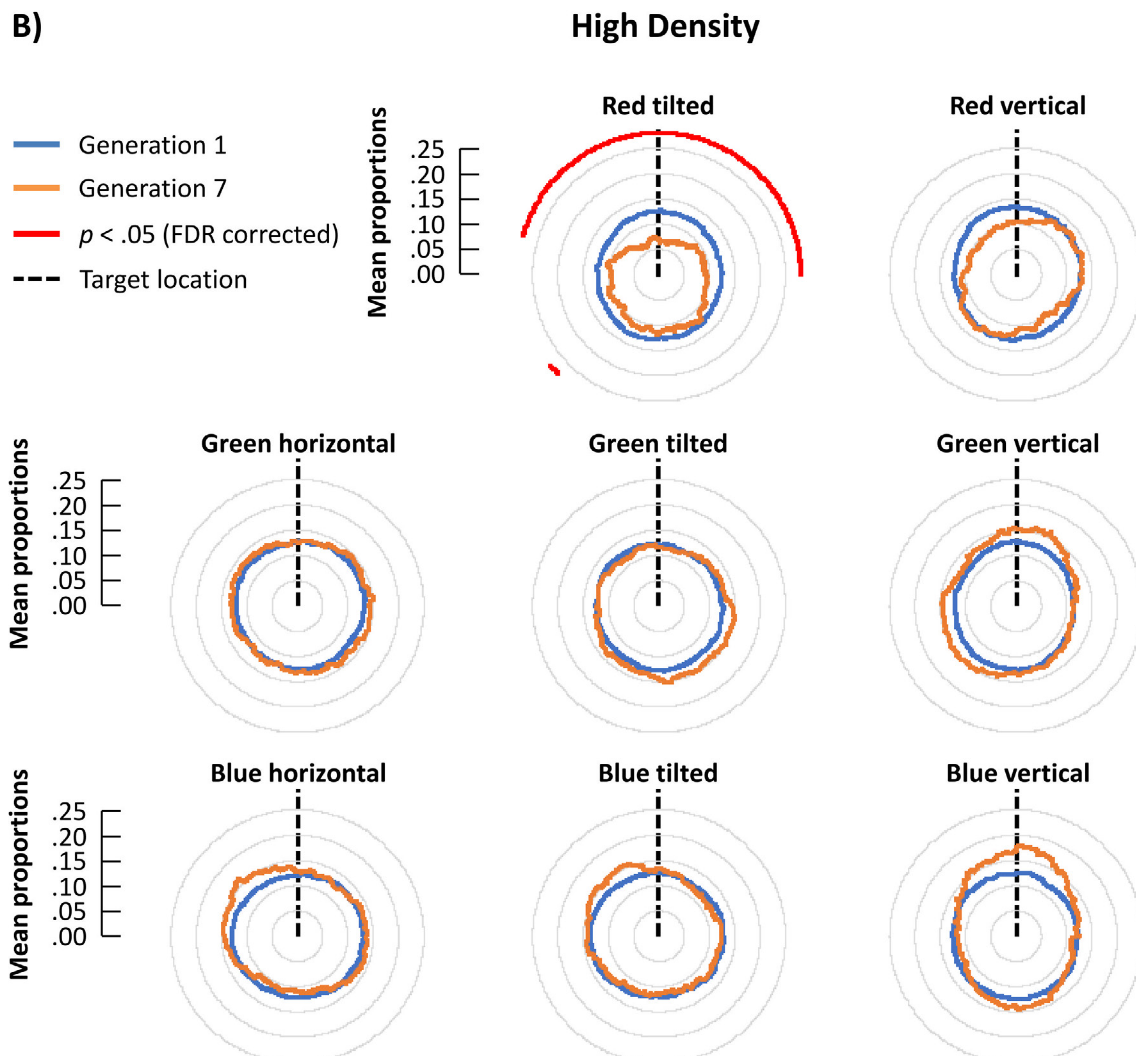

Fig. 5. (*continued*)

3.1. Methods

3.1.1. Participants

Twelve participants with normal or corrected-to-normal vision participated in the experiment, 7 male, with an average age of 25.8 years, ranging from 19 to 31 years. They were paid (€ 4 euro) or received course credits, and were naive as to the purpose of the experiment. All participants filled in a consent statement prior to the experiment. The experiment was approved by the local ethics committee of the Vrije Universiteit Amsterdam and conducted in accordance with the Declaration of Helsinki.

3.1.2. Task and stimuli

The equipment, task and stimuli were similar to those in Experiment 1 except for the following differences. First, we changed the displays such that the set of possible distractor types was reduced in one of the four quadrants of the stimulus display. That is, the possible distractor types presented in this quadrant, the critical quadrant, was reduced from 8 to 7 with the result that it could never contain any red tilted distractor. Accordingly, the possible distractor types presented in this critical quadrant consisted of red-vertical, green-horizontal, green-tilted, green-vertical, blue-horizontal, blue-tilted, and blue-vertical. The possible distractor types presented in the remaining quadrants were similar to those in Experiment 1. Fig. 6 illustrates four example displays used in Experiment 2.

Second, the red horizontal target was equally likely presented in either one of the four quadrants implying that there was a probability of 0.25 that the target was presented in the critical quadrant and a probability of 0.75 that it was presented in one of the remaining quadrants. Targets were always presented at the middle position of each quadrant (see Fig. 6) and displays were rotated in a similar vein as in Experiment 1. Finally, for each trial a new display was randomly generated by assigning distractors to all display locations.

3.1.3. Design and procedure

The experiment consisted of 2 experimental blocks of 160 trials each, one corresponding to the low-density condition and one corresponding to the high-density condition. Each experimental block was preceded by a corresponding practice block consisting of 20 trials. The presentation order of both density conditions was counterbalanced over participants. Target location was varied within blocks of trials: each experimental block consisted of 40 trials in which the target was presented in the critical quadrant and 120 trials in which the target was presented in one of the other quadrants. Trials were randomized within blocks. Each participant performed 360 trials in total, which took about 25 minutes.

3.2. Results and discussion

Practice trials were discarded from further analyses. The mean error

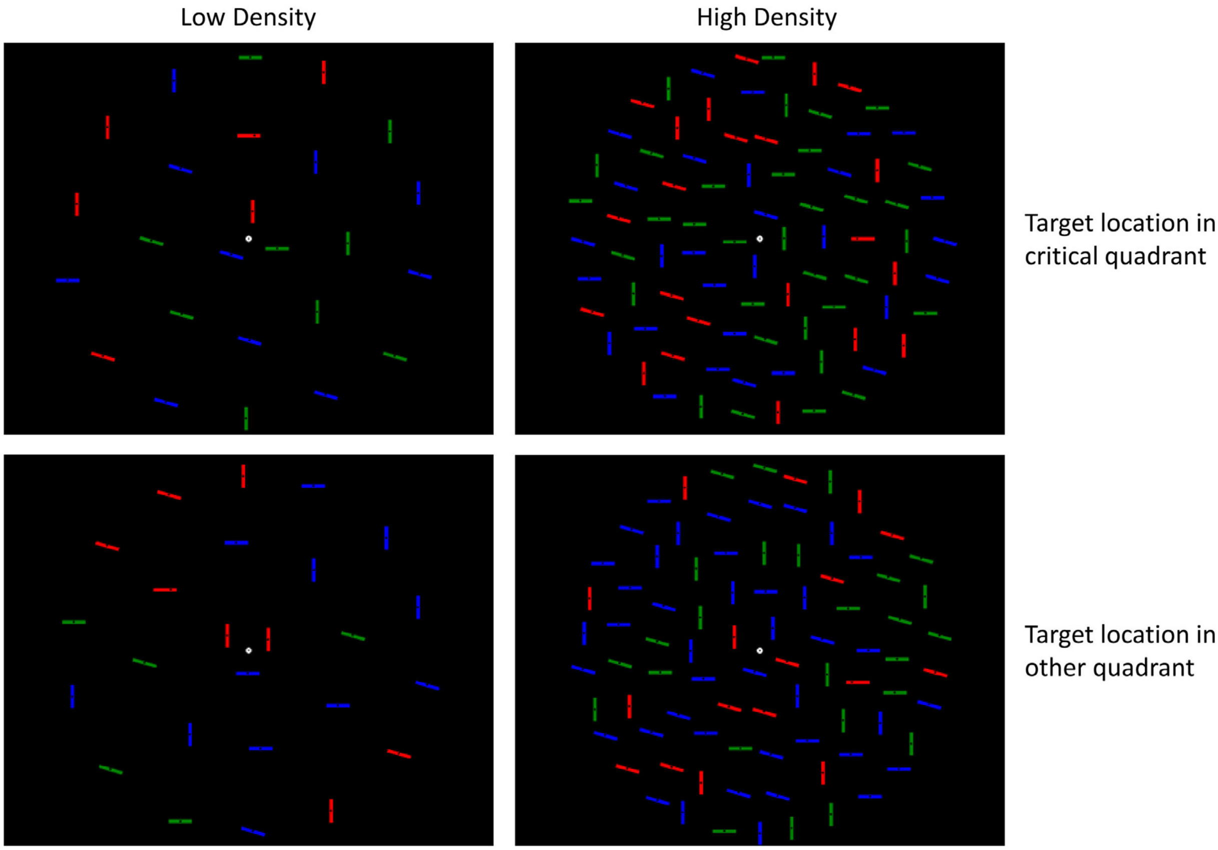

Fig. 6. Sample displays for the low-density and high-density display conditions. Participants searched for the red horizontal line. The target contained a black gap which was positioned slightly offset towards the left or right, and participants made a speeded response to the location of the gap. The target was presented in the critical quadrant (that contained no red tilted distractors), or in one of the other quadrants.

rate was 2.1%. Overall, the error rate was 1.3% lower in the high-density than the low-density condition, $F(1, 11) = 6.11$, $p = .031$, $\eta_p^2 = 0.357$, and 1.0% higher when the target was presented in the critical quadrant compared to when it was presented in one of the other quadrants, $F(1, 11) = 9.02$, $p = .012$, $\eta_p^2 = 0.451$. There was no interaction between Display density and Target location, $F(1, 11) < 1$.

Fig. 7 depicts the mean correct RTs as a function of Display density and Target location.

A repeated-measures ANOVA on the individual mean correct RTs with Density (low and high) and Target location (critical quadrant versus other quadrant) as repeated-measures factors revealed a significant effect of Density, $F(1, 11) = 114.23$, $p < .001$, $\eta_p^2 = 0.912$, as search was faster for the low-density condition (1028 ms) than for the high-density condition (1998 ms). There was a significant effect of Target location, $F(1, 11) = 20.80$, $p = .001$, $\eta_p^2 = 0.654$, showing that RT was lower when the target was located in the critical quadrant as compared to one of the other quadrants. Importantly, the two-way interaction was also significant, $F(1, 11) = 13.68$, $p = .004$, $\eta_p^2 = 0.554$. The interaction was further examined by two tailed t-tests for each density condition. For the low-density condition, the t-test yielded no significant Target location effect, $t(11) = 1.28$, $p = .228$. In the high-density condition, the t-test yielded a significant Target location effect, $t(11) = 4.26$, $p = .001$, as the RT was lower when the target was located in the critical quadrant (1902 ms) as compared to when it was located elsewhere (2094 ms).

It is important to note that even though there might have been a trade-off between speed and accuracy with respect to the main effects of Display density and Target location, there is no indication for such a trade-off regarding the interaction between Display density and Target location. Accordingly, the results show that the presence of red elements with a similar orientation as the target object are highly

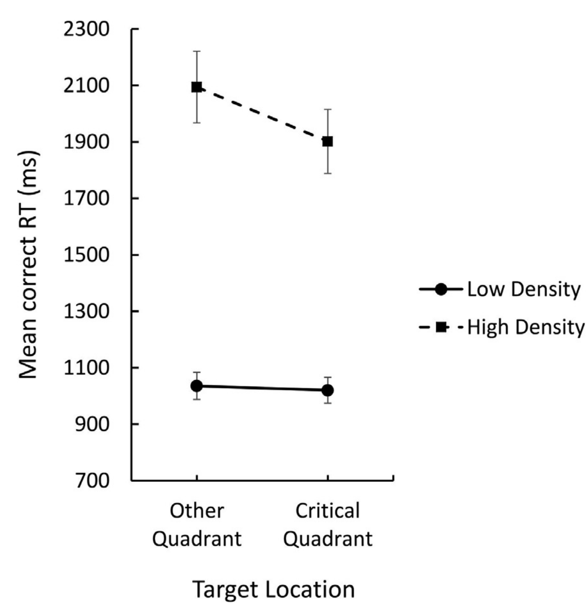

Fig. 7. Mean correct RT as a function of display density (low density and high density) and target location (critical quadrant versus other quadrant). Error bars reflect the standard error of the mean.

disruptive when presented in the vicinity of the target in the high-density condition, but not in the low-density condition (see also Experiment 1). This suggests that attentional selection in high-density displays more strongly relies on local feature contrast differences whereas selection in low-density displays does not.

4. General discussion

The aim of the present study was to examine whether a change in display density leads to a change in attentional guidance in heterogeneous displays. In Experiment 1 display density was manipulated across two conditions: the low-density and the high-density condition. A genetic algorithm was used to explore the relative importance of individual stimulus features in visual search in both conditions.

The results show that in the low-density condition, there was a general decrease in the proportion of red distractors, irrespective of orientation. In the high-density condition, the proportion of red tilted distractors decreased whereas this was not the case for the red vertical distractors. Moreover, the spatial analyses showed a substantial difference between both density conditions. Whereas the displays in the low-density condition were nearly entirely filled with blue and green distractors, there were still multiple red elements in the high-density displays although the red tilted distractors were hardly located around the target position.

In Experiment 2 we replicated the differential spatial effect across display density using a factorial design in which we systematically manipulated the location of the target such that it was either presented in a quadrant containing all different types of distractors (like in Experiment 1) or all except the red tilted ones. The results showed that the RT was independent of target location in the low-density whereas it was not in the high-density condition. In this latter condition search clearly suffered from the presence of red tilted distractors in the vicinity of the target.

Overall our results are very similar to those of Rangelov et al. (2017) who also found that search in dense displays tends to rely on local feature discontinuities whereas this was not the case for search in sparse displays. However, Rangelov et al. (2017) had observers search for a feature-singleton target among a uniform set of distractors. Accordingly, their conclusions related to search in homogeneous displays and how guidance in such displays differs across display density. In the present study we used heterogeneous displays presumably ruling out the possibility to rely on local discontinuities. Yet, our results showed that search in high-density displays also profits from the presence of local discontinuities and thus appears to rely at least partly on salience-driven rather than feature-driven guidance. The relevance of local discontinuities in visual search has also been demonstrated by Nothdurft (1993) who reported very efficient search when targets displayed local feature contrast even when the distractors were highly heterogeneous. In this study observers were presented with dense displays consisting of elements varying across two dimensions. For instance, elements in the so-called orientation and color displays varied across orientation as well as color but were arranged such that they formed continuous orientation and color flows. The task of observers was to indicate the presence of a single vertical line. The basic finding was that search was only efficient when the target displayed local feature contrast. When the target was not marked by local feature contrast it failed to produce pop out. Even though the target used in this study was essentially a feature-singleton, the displays were highly heterogeneous which is typically associated with inefficient search. Yet, again, the efficiency was demonstrated to be critically dependent on the presence of a local contrast at the target location rather than on the overall target-distractor similarity. The relevance of local feature contrast in determining the extent to which people rely on salience in target search is also evident from studies measuring eye movements in real-world images (Anderson & Donk, 2017; Anderson et al., 2015; Anderson, Donk, & Meeter, 2016; Einhauser, Rutishauser, & Koch, 2008; Itti & Koch, 2000; Itti, 2006; Parkhurst et al., 2002). Real-world images are typically highly heterogeneous and often contain multiple more or less equally salient locations. Yet, visual selection has been demonstrated to be at least partly salience-driven, in particular immediately after the presentation of the image (Anderson & Donk, 2017; Anderson et al., 2015, 2016), suggesting again that local feature contrast may indeed play a role in heterogeneous displays.

It is interesting to note that although crowding enhances identification thresholds for orientation much stronger than those for color (Van den Berg et al., 2007), the role of orientation was larger in high-density than in low-density displays. A possible explanation for this finding might have been related to a stronger role of orientation *contrast* in high-density compared to low-density displays. For instance, visual search for an orientation singleton generally becomes more rather than less efficient when display density increases (Nothdurft, 2000; Sagi & Julesz, 1985). Texture segmentation has also been reported to be more efficient in dense than in sparse displays (Nothdurft, 2000; Wolfe, 1992). Accordingly, it seems that the importance of local orientation contrasts increases with display density and contributed to guidance in high-density displays whereas it did not affect search in low-density displays.

Our results are comparable to those of previous studies using a Genetic Algorithm as a way to investigate how search proceeds through complex heterogeneous displays. In Van der Burg et al. (2015) target and distractors were similar to those in the present study but displays were denser. Their results also showed a substantial decrease in the number of red titled distractors in the target area, whereas the number of red vertical distractors did not decrease in this area. These findings are in line with the present results.

Over the years there has been much debate about whether attention is ultimately controlled in a bottom-up salience-driven or top-down feature-driven fashion (Bacon & Egeth, 1994; Folk et al., 1992; Folk, Leber, & Egeth, 2008; Leber & Egeth, 2006; Schreij, Owens, & Theeuwes, 2008; Theeuwes, 1992, 2004; van Zoest & Donk, 2004). Nowadays, most researchers agree that attentional deployment can be controlled by both salience and features, but also other factors, including selection history (Awh et al., 2012), reward, and scene attributes (see Wolfe & Horowitz, 2017 for an overview). That is, the classical dichotomy between bottom-up and top-down control has become less stringent and attentional control is now believed to be affected by multiple mechanisms. For instance, when people search for a specific target in the presence of an irrelevant distractor which was previously associated with a monetary reward, search is slowed down in comparison to when the distractor was previously not rewarded (Anderson, Laurent, & Yantis, 2011). Results like these show that reward constitutes an important modulating factor in the guidance of attention. However, despite the consensus that attention can be driven by different processes, it is remarkable to note that display density is typically not considered to be a key factor in determining the mode of control (but see Rangelov et al., 2017). Indeed, in order to investigate attentional control mechanisms in visual search, researchers have commonly used a standard visual search task in which participants search for a target among a varying number of distractors. The slope of the function relating RT to the number of distractors is then used to determine whether search was efficient or not, and search efficiency is subsequently taken as an index to infer the attentional control mechanism search behavior was based on. Importantly, varying display size typically goes along with changes in display density. As shown in the present study, sparse and dense displays may lead to fundamentally different search modes. Accordingly, rather than just manipulating display density as a means to investigate attentional selection across different display sizes, display density might well be considered to be a serious candidate for guidance. Just like a previously rewarded color may guide attention more effectively towards that color, increasing display density may guide attention more effectively to local feature contrast.

In conclusion, our results indicate that feature properties of the target may play a more prominent role in low-density displays and that the way the target is embedded in its visual context is a determinant factor of target saliency in high-density displays. This suggests that the role of salience-driven attentional guidance is larger in dense than sparse displays even in the absence of display homogeneity. To date, the vast majority of studies have focused on visual search using rather sparse displays. It is therefore questionable whether results in these studies generalize to more heterogeneous environments, like natural scenes. It is clear from the present study that search through complex displays is guided differently than through simple displays. We therefore believe that we must move our research to more complex environments. A genetic algorithm is an excellent methodology to study human behavior in complex displays that is not restricted by the complexity of the design.

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Author contributions

MvdW, EvdB, & MD conceived and designed the experiments; MvdW performed the experiments; MvdW, EvdB, & MD analyzed the data; MvdW, EvdB, & MD wrote the paper. MD supervised the generation of the manuscript. All authors have approved the final article.

Declaration of Competing Interest

The authors are not aware of any conflicts of interest or competing financial interests that affect the objectivity of this work.

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