

Visual search for feature singletons: Multiple mechanisms produce sequence effects in visual search

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Selection of a feature singleton target in visual search tasks, e.g., a red target among green distractors, is very fast—as if the target “popped out” of the display. Interestingly, reaction times (RTs) sometimes even decrease with an increase in the number of distractors (while keeping the presentation area fixed), i.e., there is a negative RT/display density relationship. Furthermore, repeating—versus changing—target-defining properties across trials also speeds up RTs. The present study investigated how display density influences two similar but dissociable types of such intertrial effects, namely (a) priming of pop-out (PoP), observed when the target-defining dimension is fixed, e.g., color, and only the features of the target and distractors, e.g., red and green, vary across trials and (b) the dimension-repetition effect (DRE), observed when both the features and dimensions of the target vary, e.g., from red circle (color) to blue square (shape target) among blue circles. Experiment 1 examined PoP magnitude with sparse (three-item) versus dense (36-item) displays in conditions in which the distractors' color either (a) varied, i.e., red target, green distractors versus green target, red distractors, or (b) it was fixed (blue). Significant PoP was observed only for sparse distractors conditions. Experiment 2 investigated the DRE magnitude across display densities with distractors always being fixed: Significant DREs of comparable magnitude were observed with both sparse and dense displays. This dissociation between the PoP and DREs suggests, first, the existence of multiple mechanisms of intertrial effects and, second, that PoP is specific to low target-distractor signal-to-noise ratios when the target fails to pop out.

Introduction

At any moment, the visual world offers us a multitude of different objects, of which only some are relevant for achieving our current behavioral goals. As a consequence, any purposeful behavior requires successful selection of important and/or deselection of unimportant aspects of the visual world. In this sense, the need for stimulus selection constitutes a limiting factor for all the following—perceptual and response-related—cognitive processes, and knowing what is selected helps predict the subsequent behavior. Thus, understanding how visual selection actually works (the theme of the current special issue) is a central question in cognitive psychology. One of the most productive approaches to answering this question assumes that the perceptual system, rather than simply providing a snapshot of the visual world, generates a map of the visual scene, signaling the relative importance of each scene location (Itti & Koch, 2001; Logan, 1996; Treisman & Gelade, 1980; Wolfe, 1994). Locations are then selected for focal-attentional processing in the order of their relative importance from more to less important ones. Consequently, the question of how visual selection is achieved translates into how the relative importance, or priority, of each location is computed. The main aim of the present study was to investigate the interplay between stimulus- and organism-specific factors thought to influence priority computation.

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Determinants of priority map computation

Early accounts of priority computation conceived of the underlying processes as being relatively automatic in nature, driven primarily by the physical properties of the current scene. In particular, they assumed these processes to be highly sensitive to feature discontinuities: Spatial regions within which features change abruptly (e.g., from green to red) would receive a higher priority ranking than featurally homogenous regions (e.g., regions of green color). That feature discontinuities can guide processes of selection is consistent with the way features are coded in the primate brain. Neurons in early vision are sensitive, or tuned, to particular features (e.g., light of a particular wavelength) present in a particular subregion of the visual field (Livingstone & Hubel, 1984, 1988), that is, within their so-called receptive fields (RFs). Importantly, a neuron's output is modulated not only by the stimuli in its RF, but also by those in surrounding areas. This so-called nonclassical RF (Field, Hayes, & Hess, 1993; Li, 1999; Zhaoping, 2005) exhibits iso-feature suppression: If a stimulus in the RF is, say, an oriented bar the neuron is tuned to, the output of the neuron will be much stronger when no other bar of the same orientation is presented nearby (but outside of the RF) relative to when many such bars are present together. Via iso-feature suppression, locations with a feature discontinuity (weak suppression) will produce stronger signals relative to homogeneous areas (strong suppression).

Behavioral findings also support the notion that feature discontinuities play an important role in visual selection. The iso-feature suppression mechanisms would predict that the relative conspicuity of any location will be modulated by what and how much stimulation is available: A green item presented in isolation would be more conspicuous than the same item presented along with other green items nearby. In other words, the relative priority of any single item decreases as the number of featurally similar items in its surround increases. If, in a particular experimental setting, green items are made task-irrelevant, or distractors, presenting more or less green distractors within a fixed display area should result in shorter reaction times (RTs) for dense (many distractors) relative to sparse (few distractors) displays by virtue of any single distractor producing weaker priority signals with high-density relative to the low-density displays. Using a so-called “compound-search” task and keeping the presentation area constant, Bravo and Nakayama (1992) reported the expected speeding up of responses with an increase in the number of distractors. In their task, participants were presented with arrays of colored diamonds, one of which (target) was uniquely colored (color = target-defining property). Each diamond was

missing the left or the right corner (side of missing corner = response-defining property). The task was to select the target (by color) and report the missing corner. Bravo and Nakayama explained the negative RT/display density relationship by assuming that, for sparse displays containing only few items, each single item, whether it is the target or a distractor, is highly conspicuous, rendering the target itself relatively difficult to select; with more dense displays, by contrast, the relative conspicuity of the distractors decreases, effectively increasing the conspicuity of the target.

Although feature discontinuities frequently coincide with behaviorally relevant locations in the visual world, this is not always the case; for example, a lion hiding in the grass would not be very conspicuous but highly relevant. Thus, computing only feature discontinuities does not necessarily allow for adaptive visual selection in all scenarios. To detect behaviorally relevant but relatively inconspicuous objects (e.g., a camouflaged animal), visual selection processes should be able to attach higher priority to their locations compared to those exhibiting strong feature discontinuities. To what extent the cognitive system is able to ignore signals from the physically most conspicuous locations and instead select less conspicuous but behaviorally more relevant locations is still a matter of debate. One position holds that selection is stimulus-driven and little, if at all, influenced by the behavioral relevance of the stimulation (Theeuwes, 1991, 1992; for a recent review, see Theeuwes, 2010). Consistent with the idea that visual selection is strongly influenced by the stimulus properties are the findings that RTs are slower when a task-irrelevant but conspicuous additional singleton is presented together with the target relative to when it is absent, suggesting that focal attention is indeed summoned to the location of the highest conspicuity (but see Müller, Geyer, Zehetleitner, & Krummenacher, 2009, and Zehetleitner, Goschy, & Müller, 2012a, who demonstrated that stimulus-unspecific factors also influence this effect).

Other findings, however, show that the priority of physically-the-same stimuli is additionally dependent on (stimulus-unspecific) organism-specific factors. Two sets of findings provide support for this position: priming of pop-out (PoP) and dimension-repetition effects (DREs). Both these effects are related to the intertrial sequence of stimulus properties and have mostly been studied in singleton feature search tasks. In this type of task, a target item is presented in an array of multiple, homogeneous nontarget items, among which the target differs from the distractors in a single feature (e.g., a singleton color target: a red item among green items). The locations of feature singletons are thought to always produce strong feature discontinuity signals and, consequently, are assigned the highest priority on the priority map. In this scenario, the

feature singletons would always be the first item selected, irrespective of how many items are presented—as if the singleton “popped out” from the field of distractors (e.g., Wolfe, 2007). Accordingly, feature singleton search is often referred to as a pop-out search. Two different strands of research have shown that the time required to respond to such a pop-out item on a given trial is not only dependent on the target’s conspicuity, but also on intertrial history, that is, on how the target was defined relative to the distractors on the preceding trial(s). Depending on what target properties vary across trials of a pop-out search task, either PoP or DREs are observed.

The present study was designed to investigate the boundary conditions necessary for the PoP and DREs to arise. A particular focus was on contrasting different theoretical accounts of intertrial effects, namely, accounts that postulate a unitary mechanism versus accounts postulating that different intertrial effects reflect the dynamics of multiple mechanisms, all of which would be sensitive to the recent trial history.

Intertrial effects in pop-out search tasks

In a typical PoP paradigm, the dimension of the target is fixed across trials. More precisely, the target is always, for instance, a color singleton, and only the target features vary, say, the target is either red or green. Repeating the exact target feature across two trials (e.g., red → red) typically results in shorter RTs relative to target-feature changes (e.g., green → red). Accordingly, intertrial effects are feature-specific in nature. Because repeating the target feature is thought to enhance the priority signal at the singleton location, which, in turn, would reduce the time necessary for the target to pop out (Töllner, Zehetleitner, Gramann, & Müller, 2011), the feature-specific intertrial effect has been termed PoP (Maljkovic & Martini, 2005; Maljkovic & Nakayama, 1994, 1996, 2000).

By contrast, in a typical DRE paradigm, the defining dimension of the singleton varies across trials; for instance, in some trials, the target is a color-defined singleton; in others, it is a shape-defined singleton. Unlike a typical PoP paradigm in which there are feature swaps between the target and the distractors, the distractors in a DRE paradigm are typically fixed and remain the same throughout the experiment. Similar to the PoP effect, repeating the dimension of the singleton across trials (e.g., color → color) produces shorter RTs relative to dimensional changes (e.g., shape → color), an effect referred to as DRE (Found & Müller, 1996; Müller, Krummenacher, & Heller, 2004; Müller et al., 2010). Critically, the DRE can be dissociated from the PoP effect: RTs are comparable for full target repetitions (e.g., red → red) and

dimension repetitions with feature changes (e.g., green → red), and both are faster relative to dimension (and associated feature) changes (e.g., square → red; see Found & Müller, 1996). In other words, DREs persist across feature changes within the target-defining dimension; that is, the effect is dimension- rather than feature-specific in nature.

Because stimulus properties in both PoP and DRE paradigms are controlled for—with only the recent (intertrial) history varying across repetitions and changes—both effects strongly suggest that priority computation does not solely rely on stimulus factors, but that organism-specific factors, especially memory, matter too. Early accounts of both PoP and DREs assumed these effects to reflect processes of priority map computation. For instance, Maljkovic and Nakayama (1994, 2000) attempted to account for PoP effects by assuming the existence of an implicit-memory buffer that keeps track of the sequence of previously relevant features. The contents of this buffer would then directly influence priority computation in such a way that computation would be faster for targets defined by repeated features (i.e., features already stored in the buffer) relative to other features, resulting in PoP.

Similarly, Müller and colleagues (Müller & Krummenacher, 2006; Müller et al., 2010; Zehetleitner, Krummenacher, & Müller, 2009) developed a dimension-weighting account (DWA) to explain the DRE. The DWA assumes priority computation to consist of three processing steps: (a) feature-specific representation of the visual scene (feature maps), (b) dimension-specific (feature-discontinuity) maps, and (c) a master map of priority. These three levels are hierarchically organized in such a way that the output of the lower levels serves as input to the higher, more abstract levels from feature maps via dimension maps to the search-guiding master map. Critically, the DWA hypothesizes that the efficiency of signal transmission from separate dimension maps to the master map is sensitive to, or weighted by, the previous relevance of any given dimension. If, say, color was relevant on trial $n - 1$, the weight for color is increased (and that of nonrelevant dimensions correspondingly decreased), allowing for faster priority computation should the relevant dimension on trial n also happen to be color, resulting in DREs.¹

Theoretically, substantial intertrial effects observed in pop-out search tasks would require that models of automatic, stimulus-driven visual selection are revised; that is, they would need to incorporate influences of other, organism-specific factors. However, rather than making priority computation “smarter,” it is also possible to assume that the PoP and DREs arise from later, post-selective stages. Such accounts were proposed for both the PoP (Huang, Holcombe, & Pashler,

2004; Huang & Pashler, 2005) and the DREs (Cohen & Magen, 1999; Mortier, Theeuwes, & Starreveld, 2005). According to post-selective accounts of the intertrial effects, visual selection is primarily stimulus-driven (i.e., feature discontinuity-driven) while the organism-specific factors, such as recent trial history, play a role only following the stage of visual selection. However, because the existence of post-selective mechanisms does not a priori exclude the possibility of preselective mechanisms sensitive to intertrial sequences, the most recent theoretical work has recognized the pre- versus post-selective dichotomy as being unsatisfactory. Rather, current models of both the PoP (Lamy, Yashar, & Ruderman, 2010; Yashar & Lamy, 2011) and DREs (Rangelov, Müller, & Zehetleitner, 2011a, 2011b, 2012; Zehetleitner, Rangelov, & Müller, 2012) postulate the existence of *multiple* mechanisms sensitive to intertrial sequences. Some of these would be preselective, assuming that “smart” priority computation processes are possible to an extent (for a similar distinction between “dumb” and “smart” priority signals, see Bisley & Goldberg, 2010). Note, though, that multiple-mechanism accounts of PoP and DREs have, thus far, been developed independently, each addressing primarily one type of effect. Accordingly, exactly how the explanations of one and the other type of effect relate to each other remains an open issue. On the one hand, it is possible that the same mechanisms give rise to both PoP and DREs; on the other hand, it could be that the two types of effect have altogether different origins. Based on the results of the present study, a more detailed notion of the relationship between the mechanisms driving the PoP and DREs is put forward in the Discussion.

Single versus multiple mechanisms of intertrial effects

While the multiple-mechanism approach can resolve some of the long-standing debates in the literature, it comes at the expense of increased complexity, and might appear rather unwieldy. With this in mind, a different theoretical account, the ambiguity resolution (AR) hypothesis (Meeter & Olivers, 2006; Olivers & Meeter, 2006) was proposed, according to which intertrial effects index processes of AR. On that account, when the task is easy (or unambiguous), no resolution is necessary, and no intertrial effects are observed. However, when some paradigm properties are ambiguous, for instance, when it is unclear which task should be performed or what the target is or which response should be given, AR mechanisms are activated. These mechanisms, in turn, are sensitive to the recent history, giving rise to intertrial effects. To illustrate, because in PoP paradigms targets alternate

randomly across trials, it is ambiguous exactly what the target-defining feature is. As a consequence of this ambiguity, the representation of the current target feature is strengthened when the feature repeats, giving rise to PoP (Olivers & Hickey, 2010). The AR hypothesis deals with the pre- versus post-selective dichotomy by assuming that the *sources* of ambiguity can be situated at either pre- or post-selective processing stages. But, irrespective of the exact source of the ambiguity, any of these would suffice to trigger resolution processes. In this sense, the AR offers an appealing theoretical alternative to the multiple-mechanism approach in that it implies a uniform mechanism that can be triggered from multiple processing stages.

For the AR hypothesis to be a real alternative to the multiple-mechanism approach, it must assume that all sources of ambiguity are resolved in a similar way. Should each ambiguity be resolved by means of its own, that is, by a source-specific AR mechanism, there would be no formal difference between the AR hypothesis and the other, multiple-mechanism approaches. Furthermore, the existence of several source-specific ambiguities would render the explanatory power of the “ambiguity” concept questionable. One of the goals of the present study was to compare and contrast predictions derived from the AR hypothesis (interpreted as a single-mechanism account) and the multiple-mechanism approach.

For one of their experiments, Meeter and Olivers (2006, experiment 1) hypothesized that display density should influence how un-/ambiguous it is to discern the feature singleton target. With sparse displays (e.g., three items in the display), typically used in the PoP paradigm, feature-discontinuity processes would yield strong priority signals for both the singleton target and nonsingleton distractors, rendering the target more difficult (or ambiguous) to discern; accordingly, the resulting PoP effects would be substantial. Conversely, an increase in display density should render the target less ambiguous and, thus, easier to find, resulting in weaker PoP effects. That PoP magnitude was indeed negatively related to display density was taken by Meeter and Olivers to provide support for their AR hypothesis (similar effects were also reported by Yashar & Lamy, 2011).

Purpose of the study

It is important to note that, in the AR hypothesis, both the PoP and DREs would index the same ambiguity resolution processes. A typical PoP paradigm is ambiguous with regard to (a) where in the display the target is located and, owing to the possibility of target and distractor feature swaps, (b) what the target-defining and (c) distractor-defining

properties are in a given trial. Similarly, a typical DRE paradigm is ambiguous with regard to (a) the target location, (b) the target-defining dimension, and (c) the target-defining feature. If all intertrial effects originate from a single ambiguity resolution mechanism and become manifest (Olivers & Meeter, 2006) under conditions of sufficiently high ambiguity, then manipulation of paradigm properties known to decrease ambiguity (e.g., display density) should result in comparable modulations of both the PoP and DREs. In other words, interactions among display density and target sequence should be comparable for the PoP and DREs. Differential modulations between the PoP and DREs would be indicative of separate origins (and underlying mechanisms) of the respective types of intertrial effect.

The present study was designed to examine whether or not display density interacts in a similar way with (a) PoP magnitude when distractors are variable (Experiment 1), (b) PoP magnitude when distractors are fixed (Experiment 1), and (c) DRE magnitude (Experiment 2). As typical DRE paradigms keep the distractor-defining features constant across trials, little is known about how DREs co-vary with changes of the distractors, and a systematic investigation of this issue would require a separate study.² Thus, as the aim of the present study was to directly compare the PoP and DREs, we opted for fixing the distractors in the PoP paradigm (Experiment 1), rather than varying distractors in the DRE paradigm (Experiment 2). To foreshadow the results, we observed stark dissociations between experimental conditions in which, according to the single-mechanism account, comparable ambiguity should have produced comparable findings.

Methods

Experiments 1 and 2 used similar experimental setups and stimulus materials. The critical difference between the two experiments was that in Experiment 1, the target-defining property was fixed (color) and the target features varied within dimension (e.g., red or green); thus, Experiment 1 tested feature-specific intertrial effects or PoP. By contrast, in Experiment 2, the target could be either a color or a shape singleton, resulting in dimension-based intertrial effects or DREs.

Participants

Two different groups of 16 participants each took part in Experiment 1a (mean age 25 years, 11 females) and Experiment 1b (mean age 26 years, 14 females), respectively, and another group of 16 observers (mean

age 24, 11 females) participated in Experiment 2, all in return for a monetary compensation or course credits. All participants had normal or corrected-to-normal visual acuity and normal color vision, confirmed with Ishihara color plates. All were naïve with respect to the purpose of the experiment, yet all had extensive experience with psychophysical experiments.

Apparatus

The experiments were controlled by a Dell PC running under the Windows XP operating system. The stimuli were presented on a 19-in. CRT monitor with a screen resolution of 1024×768 pixels and a refresh rate of 85 Hz. The experimental software was custom written in PsychoPy psychology software for Python (Peirce, 2007, 2009). Head-to-monitor distance was 56 cm, controlled by means of a chin rest. Participants responded by pressing the left or right mouse button with their left- or right-hand index finger, respectively.

Procedure

The experiments were run in a dim, sound-attenuated experimental cabin. In both Experiments 1 and 2, participants performed a compound-search task. Stimulus arrays, consisting of several distractors and one feature singleton target, were presented until either response or maximally for 1500 ms. Participants were instructed to select the target and report a different, response-defining property of the target. Both response speed and accuracy were stressed. In case of response errors, the word “Error!” was presented for 1000 ms. Participants completed 720 trials in four sessions separated by a short break in Experiment 1 and 480 trials in two sessions in Experiment 2. Overall, Experiment 1 took about 1.5 hr and Experiment 2 about 1 hr to complete.

Stimuli

In Experiment 1, similar to Maljkovic and Nakayama (1994), the target-defining dimension was color with the target being either a single red (CIE xy .255, .071) or a single green (.358, .021) item. The target color was chosen randomly in every trial. In one experimental session, the distractors' color could vary; thus, if the target was red, distractors were green and vice versa. In a different session, the distractor color was fixed across trials: It was always blue (.387, .133). Stimulus luminance was 51 cd/m^2 for all three colors. Individual items subtended an area of $1.3^\circ \times 1.3^\circ$ of visual angle. Stimulus arrays consisted of individual items arranged

around three (imaginary) concentric circles (with radii of 2.5°, 5.0°, and 7.5° of visual angle, respectively); the maximum number of items presented on the inner, intermediate, and outer circles were six, 12, and 18, respectively. The target always appeared at one randomly chosen position on the middle circle. Two different display densities were used, which were fixed per experimental session: sparse (three) and dense (36 items). In sparse displays, the two distractors presented (in addition to the target) were also located on the middle circle at positions equidistant from the target.

In Experiment 1a, individual items were diamond-shaped elements (Figure 1, left panel). A small part on either the left or the right side of every diamond was missing (response-defining feature); participants had to report which side was missing from the target diamond by pressing the respective mouse button. This task will be referred to as a *shape-discrimination* task. By contrast, the stimulus material used in Experiment 1b (Figure 1, right panel) similar to Töllner, Gramman, Müller, Kiss, & Eimer (2008; see also Zehetleitner et al., 2012b), striped circles were used instead of diamonds. The orientation of the stripes—vertical or horizontal—varied among the presented items. Participants were to

select the singleton target and report the orientation of the stripes (response-defining feature) by pressing respective mouse buttons. This task will be referred to as an *orientation-discrimination* task. Similar to Experiment 1b, striped circles were also presented in Experiment 2. Critically, however, the target-defining dimension was allowed to vary in Experiment 2: The target was either a color-defined singleton (red; the same as in Experiment 1) or a shape-defined singleton (square). Furthermore, the distractors' color was always blue (the same as in Experiment 1); that is, it was fixed for the whole experiment. Different possible stimulus-to-response mappings were counterbalanced across participants in all experiments.

Combinations of two display densities (sparse vs. dense) and distractor variability (variable vs. fixed) yielded four experimental conditions in Experiment 1, which were performed in separate experimental sessions. In Experiment 2, the distractors were fixed, yielding two conditions (sparse vs. dense displays), which were also run in separate sessions. The order of sessions was counterbalanced across participants.

The exact target feature (red vs. green in Experiment 1; red vs. square in Experiment 2) was randomly chosen

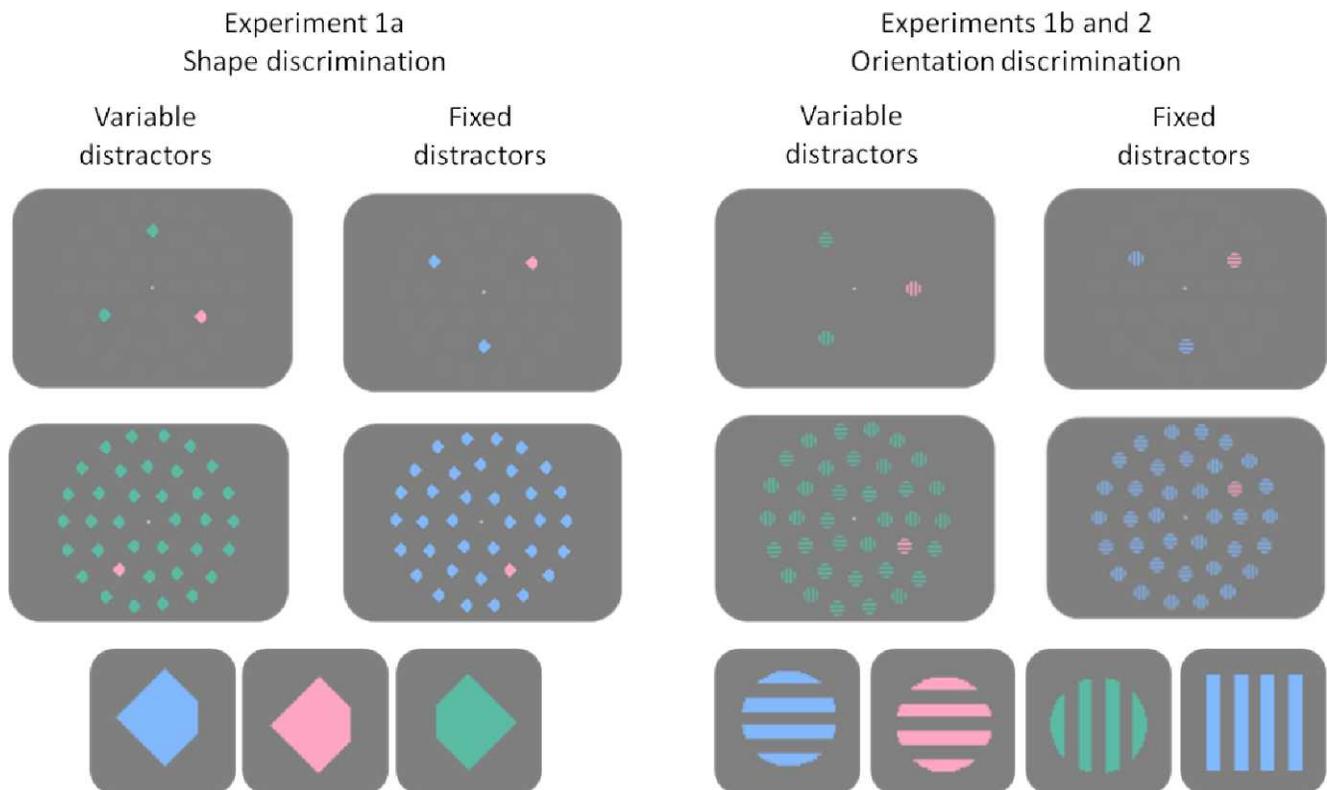


Figure 1. Illustration of sparse (upper) and dense arrays (middle) together with individual items (lower panels) serving as a target and distractors. In conditions with variable distractors, only green and red items were used, serving as both target and distractor features, respectively (e.g., red target, green distractors and vice versa). In conditions with fixed distractors, the distractor color was blue with green and red items as potential targets. In Experiment 2, instead of a *green* circle (color-defined) singleton, a blue *square* (shape-defined) singleton was used, allowing for an examination of dimension repetition effects.

in every trial. Consequently, across two trials, the target could either repeat (e.g., red → red) or change (e.g., green → red). Critically, changing the target in Experiment 1 simply changed the color of the target while the target-defining dimension—color—remained the same. Thus, the sequence effects observed in Experiment 1 would be feature-specific, or PoP, effects. By contrast, changing the target in Experiment 2 changed both the precise target feature and the target-defining dimension (e.g., shape → color). Thus, the sequence effects observed in Experiment 2 would consist of a mixture of feature- and dimension-specific or dimension-repetition effects.³

Design

The target sequence (same vs. different) was combined with other experimental conditions yielding a $2 \times 2 \times 2$ design (distractor variability \times display density \times target sequence) for Experiment 1 and a 2×2 design (display density \times target sequence) for Experiment 2.

Results

Data preprocessing

Only trials with the red target, which were common to both experiments, were analyzed. Mean error percentages were computed individually per participant per experimental condition. In Experiment 2, one participant made about 20% errors in the sparse condition and was therefore excluded from further analyses. For RT analyses, only pairs of consecutive trials ($n - 1$ and n) with correct responses were considered. Additionally, the first three trials per block were considered as warm-up trials and excluded. Trials with RTs below 200 ms or above 2.5 standard deviations from the mean per participant per experimental condition were considered as outliers and removed from further analyses, resulting in a loss of 3% of the trials. The remaining trials were sorted into eight conditions for Experiment 1: distractor type (variable vs. fixed) \times display density (sparse vs. dense) \times target sequence (same vs. different targets in trials $n - 1$ and n). On average, there were 39 trials per condition per participant. In Experiment 2, in which distractors were always fixed, there were four experimental conditions: display density \times target sequence. On average, there were 50 trials per condition per participant. Mean error rates and RTs per condition are depicted in Figures 2, 4, and 5.

Experiment 1a

Experiment 1a examined PoP effects in the shape discrimination task as a function of display density (sparse vs. dense) and distractor type (fixed vs. variable). As illustrated in Figure 2, mean RTs were faster for conditions with fixed (right panel) relative to variable distractors (left panel) with error rates exhibiting a similar pattern. Furthermore, for both variable and fixed distractors, RTs were faster for dense relative to sparse displays; that is, the search slopes were negative. Again, error rates across display densities followed the RT pattern. Most importantly, the target sequence effect (PoP) varied substantially across display-density and distractor-variability conditions with prominent PoP evident only for sparse displays with variable distractors.

These observations were confirmed by a three-way repeated-measures analysis of variance (RANOVA) of the mean RTs with main terms for distractor variability, display density, and target sequence.⁴ All three main effects proved significant: $F(1, 15) = 55.72$, $\eta^2_p = .79$, $p < 0.01$; $F(1, 15) = 62.73$, $\eta^2_p = .81$, $p < 0.01$; and $F(1, 15) = 13.17$, $\eta^2_p = .48$, $p < 0.01$ for distractor variability, display density, and target sequence, respectively. Furthermore, all two-way interactions turned out significant. The three-way interaction was also significant, $F(1, 15) = 6.92$, $\eta^2_p = .31$, $p < 0.05$. Two-way RANOVAs performed separately for variable and fixed distractors showed that the three-way interaction was due to the display density \times target sequence interaction being significant for variable, $F(1, 15) = 22.30$, $\eta^2_p = .60$, $p < 0.01$, but not for fixed distractors, $F(1, 15) = 1.09$, $\eta^2_p = .08$, $p = 0.31$. Pairwise paired-sample t tests for variable-distractor conditions (Figure 2, left panel) revealed significant target sequence effects for sparse displays (PoP = 40 ms, $p < 0.01$) but no effects for dense displays (PoP = -7 ms, $p = 0.23$). Analogous pairwise t tests for the fixed-distractor conditions (Figure 2, right panel) yielded no significant target sequence effects for either sparse (PoP = 10 ms, $p = 0.19$) or dense displays (PoP = 0 ms, $p = 0.96$).

RANOVAs of the error rates yielded results similar to the RT analyses. For variable distractors, pairwise t tests revealed a significant target sequence effect for sparse (PoP = 1.8%, $p < 0.01$) but not for dense displays (PoP = 1.3%, $p = 0.22$). For fixed distractors, the target sequence effect proved significant for sparse (PoP = 2.4%, $p < 0.05$) but not for dense displays (PoP = .3%, $p = 0.76$).

The lack of a reliable PoP effect for dense displays and displays with fixed distractors may have several causes. On the one hand, PoP may indeed be specific to sparse displays with variable distractors. On the other hand, RTs were markedly faster with fixed distractors compared to variable distractors and for dense relative

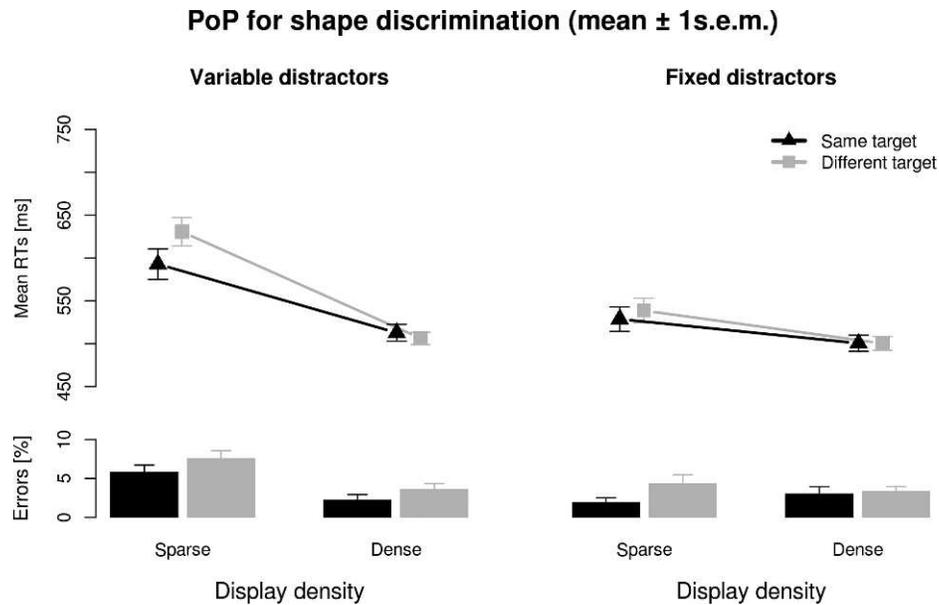


Figure 2. Mean RTs and error rates in Experiment 1a for variable and fixed distractors, sparse and dense displays, and same- (black) versus different-target (gray) sequences.

to sparse displays. It could thus be the case that the overall increase in response speed prevented the PoP effect from reaching significance. To test whether PoP magnitude co-varied with response speed, the magnitudes of the PoP effects were determined for the 25th, 50th, and 75th RT percentiles separately for the different distractor and display-density conditions. Figure 3 presents the mean PoP effects (along with their 95% confidence intervals) across these conditions. As can be seen from Figure 3, the PoP effects were substantial and significant (i.e., the confidence intervals did not include zero) only for sparse displays in variable-distractor conditions. For dense displays, the PoP was weak and did not increase with RT percentile, suggesting that the lack of a PoP effect in the overall mean RTs (see Figure 2) was not merely owing to the high response speed in this condition.

These observations were confirmed by a three-way RANOVA of the PoP magnitudes with main terms for distractor variability (variable vs. fixed), display density (sparse vs. dense), and RT percentile (25th, 50th, and 75th), which yielded the following significant effects: (a) main effect of display density, $F(1, 15) = 9.28$, $\eta^2_p = .38$, $p < 0.01$; (b) interaction display density \times distractor variability, $F(1, 15) = 8.49$, $\eta^2_p = .36$, $p < 0.05$, and interaction display density \times RT percentile, $F(2, 30) = 3.66$, $\eta^2_p = .20$, $p < 0.05$; (c) the interaction density \times variability \times RT percentile was marginally significant, $F(2, 30) = 2.93$, $\eta^2_p = .38$, $p = 0.07$. Separate analyses of the variable- and fixed-distractor conditions revealed a significant main effect of display density, $F(1, 15) = 16.70$, $\eta^2_p = .53$, $p < 0.01$, as well as a density \times RT percentile interaction, $F(2, 30) = 8.65$, $\eta^2_p = .37$, $p < 0.01$, for variable distractors (Figure 3, left panel). The

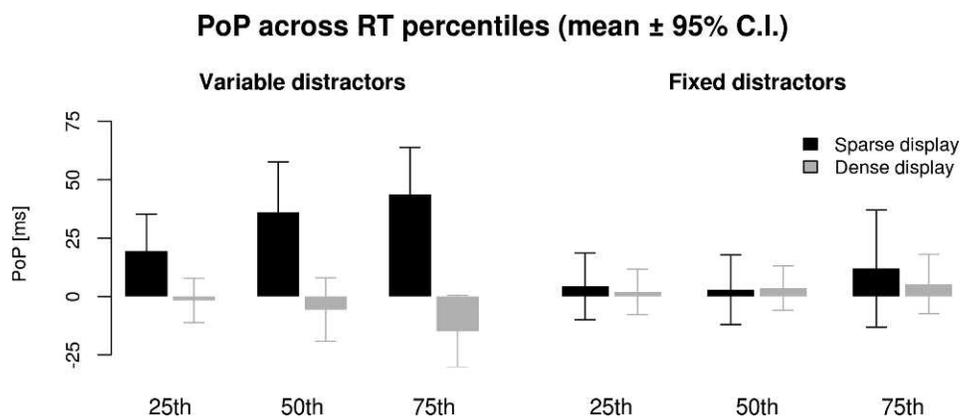


Figure 3. PoP magnitude in Experiment 1a for variable and fixed distractors, separately for sparse and dense displays and RT percentiles. Conditions in which the error bars do not include zero are significant at $p < 0.05$.

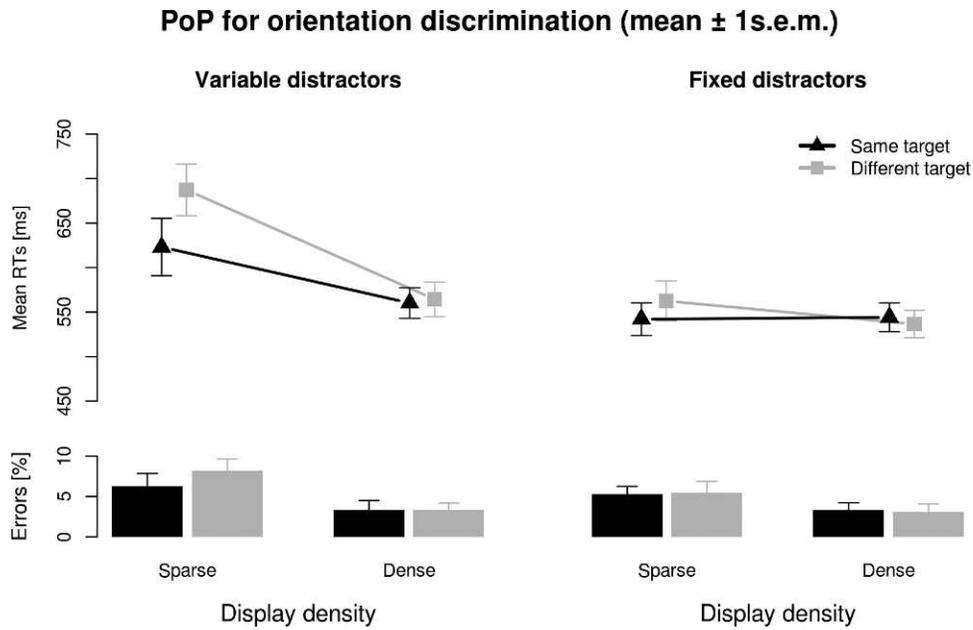


Figure 4. Mean RTs and error rates in Experiment 1b for variable and fixed distractors, sparse and dense displays, and same- (black) versus different-target (gray) sequences.

density \times percentile interaction was due to the fact that for dense displays the nonsignificant PoP effects were constant across RT percentiles; for sparse displays, by contrast, the significant PoP effects became stronger for the higher percentiles. For fixed distractors (Figure 3, right panel) neither the main effects of density and RT percentile nor the interaction between the two reached

significance (all $F_s < 1$, all $p_s > 0.47$). Taken together, these analyses suggest that the nonsignificant PoP effects for dense displays with both variable and fixed distractors as well as the weak PoP effects for sparse displays with fixed distractors cannot be simply attributed to the overall fast responses in these conditions.

DRE for orientation discrimination (mean \pm 1s.e.m.)

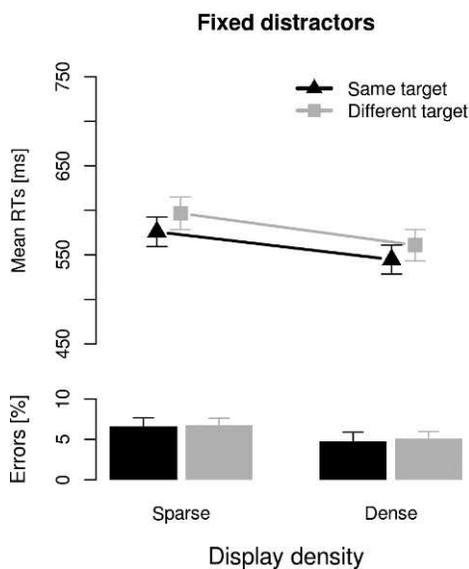


Figure 5. Mean RTs and error rates in Experiment 2 for sparse and dense displays, separately for same- (black) and different-target (gray) sequences.

Experiment 1b

Experiment 1b, too, examined for feature-specific intertrial effects (PoP) although using different stimuli from those in Experiment 1a: The stimuli were striped circles (Figure 1, right panel) with observers being required to discriminate the orientation of the stripes of the color singleton (orientation-discrimination task). All other details were the same as in Experiment 1a. Figure 4 presents the mean RTs and error rates for the conditions with variable (left) and fixed distractors (right panel), separately for the different display densities (sparse, dense) and intertrial sequences (same target, different target).

Experiment 1b yielded a pattern of mean RTs and error rates closely resembling that of Experiment 1a. Mean RTs and error rates were overall increased with variable relative to fixed distractors and for sparse relative to dense displays (i.e., the search slopes were negative). Critically, and comparable to Experiment 1a, the PoP effect was substantial only for sparse displays, and for sparse displays, it was much stronger with variable relative to fixed distractors.

A RANOVA of the mean RTs⁵ revealed all three main effects to be significant: distractor variability, $F(1, 15) = 20.46$, $\eta^2_p = .58$, $p < 0.01$; display density, $F(1, 15) = 11.90$, $\eta^2_p = .44$, $p < 0.01$; and target sequence, $F(1, 15) = 18.44$, $\eta^2_p = .55$, $p < 0.01$. Furthermore, all two-way interactions were significant: distractor variability \times display density, $F(1, 15) = 16.83$, $\eta^2_p = .53$, $p < 0.01$, indicating a stronger density effect for variable relative to fixed distractors (-99 vs. -12 ms difference between dense and sparse displays for variable and fixed distractors, respectively); distractor variability \times target sequence, $F(1, 15) = 5.71$, $\eta^2_p = .28$, $p < 0.05$; and display density \times target sequence, $F(1, 15) = 33.12$, $\eta^2_p = .69$, $p < 0.01$, indicating a stronger density effect for changed relative to repeated targets (-75 vs. -36 ms). The three-way interaction failed to reach significance, $F(1, 15) = 2.51$, $\eta^2_p = .14$, $p = 0.13$. Planned paired-sample t -test comparisons between same- and different-target sequences revealed the PoP effect to be significant for sparse displays with both variable (PoP = 64 ms, $p < 0.01$) and fixed distractors (PoP = 20 ms, $p < 0.05$) whereas there were no reliable PoP effects for dense displays (effects of 4 ms and -8 ms, $p = 0.25$ and 0.46 with variable and fixed distractors, respectively). Finally, for sparse displays, PoP was significantly reduced in magnitude with fixed than with variable distractors (20 ms vs. 64 ms, $p < 0.05$) although significant even with the former (see above).

A RANOVA of the error rates with main terms for display density, distractor variability, and target sequence yielded only a significant main effect of density, $F(1, 15) = 18.52$, $\eta^2_p = .55$, $p < 0.01$; no other main effects or interactions were significant, all F s < 2.03 , all p s > 0.17 .

In summary, in line with Experiment 1a, Experiment 1b demonstrated significant PoP effects only for sparse displays. Unlike Experiment 1a, however, in which the PoP effect was nonsignificant for sparse displays with fixed distractors, the PoP effect for this condition was significant in Experiment 1b. Importantly, though, in both Experiments 1a and 1b, the magnitude of the PoP effect in sparse displays was significantly reduced (ca. 70%) when the distractors were fixed rather than variable.

Experiment 2

The stimulus material used in Experiment 2 was the same as in Experiment 1b: striped circles. Relative to Experiment 1, the major difference in Experiment 2 was that when the target changed, both the exact target feature and the target dimension changed. Thus, the target sequence effect in Experiment 2 reflects a mixture of feature- and dimension-specific intertrial effects, referred to as DREs. Furthermore, in Experiment 2,

only fixed distractors were used. Mean RTs and error rates across different display densities and target sequences in Experiment 2 are shown in Figure 5.

As can be seen from Figure 5, RTs in Experiment 2 were overall faster with dense relative to sparse displays. Furthermore, repeating the target (dimension) resulted in faster RTs relative to changing the target with both sparse (DRE = 21 ms) and dense displays (DRE = 16 ms). Participants made 1.9% fewer errors with dense relative to sparse displays with target sequence producing no noticeable effects on the error rates. These observations were confirmed by a two-way RANOVA of the mean RTs,⁶ yielding significant main effects of both display density, $F(1, 14) = 5.28$, $\eta^2_p = .27$, $p < 0.05$, and target sequence, $F(1, 14) = 16.44$, $\eta^2_p = .54$, $p < 0.01$. The interaction between the two was far from significance ($F < 1$, $p = 0.56$). A two-way RANOVA of the error rates revealed only the main effect of display density to be significant, $F(1, 14) = 4.79$, $\eta^2_p = .25$, $p < 0.05$. Neither the main effect of target sequence ($F < 1$, $p = 0.69$) nor the sequence \times density interaction ($F < 1$, $p = 0.92$) reached significance. In summary, Experiment 2 yielded a pattern of substantial and significant display-density effects as well as substantial and significant DREs with both sparse and dense displays in terms of the mean RTs (while error rates varied only as a function of display density).

Between-experiments analyses

Overall, the results of Experiments 1 and 2 revealed the PoP and DREs to be differentially sensitive to display density with the PoP being significant only with sparse displays, and the DREs were significant with both dense and sparse displays. To test whether the observed dissociation between the PoP and DREs was due to differences in the sequence type (PoP vs. DRE) or to task differences (shape vs. orientation task), (a) mean RTs and (b) magnitudes of sequence effects (different target vs. same target) were compared across experiments.

As can be seen from Table 1, mean RTs were primarily influenced by the task with shorter RTs for shape relative to orientation discrimination. By contrast, the magnitude of the sequence effects was little influenced by the task as indicated by (a) comparable PoP and DREs with sparse displays for all tasks and (b) comparable PoP effects with dense displays in the shape and orientation tasks. Critically, the (significant) DRE with dense displays in the orientation task was significantly stronger than the respective (insignificant) PoP effect, strongly suggesting that the observed differences between the PoP and DREs were not a

Exp.	Task	Sequence type	Sparse		Dense displays	
			Mean RT [ms]	Sequence effect [ms]	Mean RT [ms]	Sequence effect [ms]
1a	Shape discrimination	PoP	533	10	500	0
1b	Orientation discrim.	PoP	552	20	540	8
2	Orientation discrim.	DRE	586	21	553	16

Table 1. Mean RTs and intertrial sequence effects across Experiments 1a, 1b, and 2, separately for sparse and dense displays. Comparisons marked by black connecting lines reached significance ($p < 0.05$).

consequence of task differences but of the different mechanisms generating the two effects.

Discussion

Taken together, present findings indicate that the PoP and DREs have qualitatively different dynamics and thus, arguably, different driving mechanisms. More precisely, manipulation of display density in the present study had a differential influence on the magnitude of PoP and DREs: While PoP appeared to be specific to sparse displays, DREs were evident, and comparable, with dense as well as sparse displays. Furthermore, as shown by between-experiments analyses, the differences between the PoP and DREs cannot be attributed to the differences in stimulus materials and, respectively, the tasks used.

Assuming a uniform AR mechanism that is triggered whenever ambiguity reaches some critical level, one would expect to observe comparable effect patterns for dense displays in all experiments. That is, if ambiguity with regard to target properties was not sufficiently high to render PoP significant for dense displays in Experiment 1, it should not have been high enough for producing significant DREs in the corresponding condition of Experiment 2 either. However, given that this was not the case (the DREs were significant with dense displays in Experiment 2!), the present results can only be explained by assuming that different types (featural and, respectively, dimensional) of intertrial transitions invoke different types of ambiguity. This assumption would be novel: To our knowledge, it has not been stated in the relevant literature. On the contrary: Olivers and Meeter (2006) referred to the concept of ambiguity to explain DREs in compound tasks, while Meeter and Olivers (2006) used the very same concept to explain PoP. Thus, it would appear that the notion of “ambiguity” (Olivers & Meeter, 2006; Meeter & Olivers, 2006) is underspecified and, so, cannot serve as a general explanatory principle.

Multiple memory mechanisms and visual search for a feature singleton

The present findings demonstrate an apparent dissociation between the boundary conditions for the PoP and DREs to become manifest. The PoP effect appears to be specific to sparse displays and disappears with very dense (36-item) displays. By contrast, the DRE is not sensitive to display density as evidenced by comparable DREs with both sparse and dense displays. Incidentally, the most frequently used display densities in PoP paradigms are sparse (up to 12 items; e.g., Becker, 2008; Hillstrom, 2000; Lamy et al., 2010; Maljkovic & Nakayama, 1994, 1996, 2000; Meeter & Olivers, 2006; Olivers & Humphreys, 2003) as compared to dense (12 and more items; e.g., Müller & Krummenacher, 2006; Rangelov et al., 2011a, 2011b, 2012; Töllner et al., 2011) for DRE paradigms.

What, then, could be the mechanisms producing this complicated interaction pattern between target sequence and display density? First, significant display density effects in all experiments suggest them to be generated by very early processes common to all conditions. As outlined in the Introduction, display density would modulate feature discontinuity signals in such a way that sparse displays result in stronger signals for each of the (few) items presented relative to the signals generated in dense displays. The strong signals for each item (i.e., distractors as well as the target) in sparse displays would render the target relatively less conspicuous compared to the same target presented in dense displays. In other words, the signal-to-noise ratio (SNR) is lower for sparse relative to dense displays. This mechanism of early distractor suppression in dense displays and the lack of it in sparse displays would account for the negative search slopes in all experiments.

Second, DRE magnitude did not vary with display density, suggesting that a mechanism other than distractor suppression generates the DRE. Such a mechanism has already been described by the DWA (e.g., Müller & Krummenacher, 2006), according to which the signal transmission from the dimension map to the master map of priorities is weighted by the recent history of the target-defining dimension. If in trial $n - 1$ the target was, say, color-defined (by whatever color feature), then the “color weight” would have been increased, speeding up transfer of any color-specific signals to the master map of priorities. If in trial n the target also happens to be a color-defined singleton (i.e., when the dimension repeats), then the attention-guiding signal will be available earlier at the master-map level compared to when the target dimension changes. Critically, the feature discontinuity signals themselves are not modified by the dimensional weights, only their transmission—which is consistent

with the additive relationship between the DRE and display density observed in the present study. Importantly, dimension weighting would operate in both PoP and DRE paradigms. However, owing to the fact that PoP paradigms use only one dimension (e.g., color), the dimensional weights would remain stable across trials. Consequently, this mechanism cannot account for PoP effects.

In contrast to the DREs, which were significant with both sparse and dense displays, the PoP proved significant for sparse displays only. Critically, the absence of PoP for dense displays cannot be attributed to a simple floor effect because (a) analysis of the PoP effect across RT percentiles for dense displays revealed no increase in PoP magnitude with increasing percentile, and (b) although mean RTs were overall longer in Experiment 1b, the PoP effect for dense displays still failed to reach significance. Thus, the boundary conditions for PoP to arise seem to be specific to low SNRs on the master map of priorities. In other words, and somewhat paradoxically given the terminology, the “priming of pop-out” effect does arise under conditions in which the target actually fails to pop out.

PoP in sparse displays

That the target in sparse displays is not the first item to be selected, that is, that it does not necessarily pop out, is supported by findings of Becker (2008), who measured spontaneous eye movements while participants performed a compound search of sparse (five-item) displays. Among other analyses, Becker reported that the target singleton was frequently not the first but, on average across trials, *only the second item* to be fixated. Because visual selection is assumed to be tightly coupled with eye movements (Deubel & Schneider, 1996), the findings of Becker suggest that the target frequently did not pop out. Going back to the PoP effect with variable distractors in the present study, failing to select the target first and (accidentally) responding to the response-defining property of the first selected (distractor) item would have incurred a marked drop in accuracy. Consequently, to maintain acceptable accuracy levels, deciding whether or not the selected item is indeed the target would have to precede any response-related decisions. Along the rationale proposed by Huang et al. (2004), post-selective target-feature checking would be faster when the target repeats (i.e., matches an episodic-memory trace) relative to when it changes. An important assumption is that the checking process considers both what the *present* target is and what the *previous* target was (does the present target match a trace laid down in the previous task episode?). The

decision that the selected item is indeed the target is then reached faster when the target is the same across trials relative to when there is a change, resulting in feature-specific intertrial effects.

The available literature suggests that for feature-specific intertrial effects (PoP) to emerge, it is not necessary that the target *always* fails to pop out. Rather, it is likely the overall SNR in the experimental paradigm that determines whether or not the compensatory mechanism will be engaged. For example, Krummenacher, Grubert, and Müller (2010) investigated feature-specific effects in displays consisting of either a single item (i.e., sparse displays) or many items (i.e., dense displays) presented in separate experimental sessions. Of the greatest importance for the present discussion is the finding that feature-specific effects with dense displays were modified by the order in which the experimental sessions were administered: sparse → dense versus dense → sparse. Substantial intertrial effects for dense displays were observed when the dense session followed the sparse session but not the other way around. Restated in the present terms, it was as if the low SNR in the sparse displays (and associated compensatory mechanisms) generalized to the subsequent sessions even though the SNR was high with the dense displays, further supporting the notion that PoP reflects a (compensatory) fall-back mechanism for situations in which the faster/more efficient processes are prone to fail (for a similar notion see Lamy, Zivony, & Yashar, 2011). Importantly, generalizing from conditions of low to high SNR could also account for the significant PoP in dense displays reported previously (e.g., Ásgeirsson & Kristjánsson, 2011; Sigurdardottir, Kristjánsson, & Driver, 2008): Because display densities (sparse and dense) varied unpredictably across trials in these studies, it is reasonable to assume that the processes generating the PoP effect in sparse displays generalized to dense displays.⁷

PoP in dense displays

Solving the compound task on its own requires focal-attentional analysis of the target, and assuming that the analysis occurs along all target properties⁸ (i.e., both the target- and response-defining features), it is highly likely that the target-defining feature is encoded in any given trial with dense as well as sparse displays. Having to encode the target feature would predict significant PoP effects for dense displays in conditions in which task performance is less than optimal, such as trials with unusually long RTs (as with the 75% RT percentile in Experiment 1a) or when the task is rendered overall more difficult (as in Experiment 1b).

However, results of the present study show this not to be the case. Thus, the missing PoP effect with dense displays remains puzzling.

A tentative explanation for the absence of PoP with dense displays might be that the target feature from the previous trial, although potentially available, is not taken into account when performing a task. Rather, a different target property, namely, the strength of its feature contrast signal, would provide reliable evidence that the (first) item selected is indeed the target. Some evidence from our lab supports this notion. In a recent study, Rangelov et al. (2011b) mixed randomly across trials single-item (i.e., sparse) and dense displays with the display type being cued at the beginning of every trial. Independently of display type, participants reported presence/absence of a target using the same response keys for both display types. The critical finding was that while significant target sequence effects were observed across trials of the same display type there were no intertrial effects across trials with different displays. Control experiments showed that the lack of sequence effects across different displays cannot be explained in terms of simple stimulus-related differences. Thus, the findings of Rangelov et al. (2011b) would suggest that the representation of the target properties (and its effects on subsequent trials) can vary—such that it may be feature-specific (when the SNR is low) or feature-unspecific (when the SNR is high).

Three mechanisms of finding the feature-singleton target

In summary, the present findings, together with the available literature, suggest that different behavioral effects, which were previously all considered to reflect/influence the computation of the priority map, may have entirely different underlying mechanisms. The results are consistent with the assumption that three separate mechanisms give rise to the complicated target sequence \times display density interactions observed in Experiments 1 and 2. The display density effects would reflect *iso-feature suppression mechanisms* during computation of the feature discontinuity signals. The DREs would reflect weight interplay between previously relevant and irrelevant dimensions, influencing *signal transmission* from dimension-specific maps to the supra-dimensional (master) map of integrated priority signals. Finally, a greater portion of the PoP would reflect a *compensatory process* when the master map of priorities does not provide sufficient guidance to reliably select the target.

Conclusions

The results of the current study showed that assuming a uniform mechanism generating intertrial effects in all experimental conditions for which such effects have been reported cannot explain the observed dissociation between the effects with DREs manifesting with both sparse and dense displays and PoP manifesting only with sparse displays. The multiple-mechanism approach, by contrast, appears to offer the most parsimonious explanation. Admittedly, the greater explanatory power of the latter approach comes at the cost of increased complexity. However, at least in the context of the present study, such complexity appears warranted.

The most important implication of the missing PoP effect with dense displays, which cannot be attributed to a simple floor effect, is that the cognitive system appears not restricted to one default representational mode even in tasks as simple as feature-singleton search. Rather, the choice of the processes varies from feature-specific to feature-unspecific so as to optimize performance speed and accuracy. In this sense, the cognitive system acts in a “lazy” way, attempting to minimize the workload while maximizing the effect.

Keywords: feature singleton search, pop-out, priming of pop-out, dimension-repetition effect

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Footnotes

¹Importantly, on this account, the weight would be increased for the target-defining dimension as a whole, explaining why a feature change within a repeated dimension does not affect RT performance.

²Work from our lab (Krummenacher & Müller, 2013) shows that keeping the target fixed across trials

while changing the distractor properties in such a way that the target-defining dimension either repeats or changes, still produces DREs.

³By virtue of not having a baseline condition in which the target neither repeated nor changed across trials, it was impossible to dissociate target repetition from target change effects. Consequently, labeling the effect as a *repetition* or *change* effect is arbitrary; the interested reader may refer to Rangelov et al. (2012), in which the reasons for choosing the label DRE are elaborated.

⁴A similar RANOVA with target type (red vs. green) added as a factor revealed neither the main effect of the target type, $F(1, 15) = 2.42, p = 0.14$, nor any of its interactions with distractor variability, display density, and target sequence, all $F_s < 1.89$, all $p_s > 0.19$, to be significant, arguing that both target types were processed similarly.

⁵A similar RANOVA with target type (red vs. green) added as a factor revealed neither the main effect of target type, $F(1, 15) = 2.94, p = 0.11$, nor any of its interactions with distractor variability, display density, and target sequence to be significant, all $F_s < 1.30$, all $p_s > 0.27$, suggesting that the different targets were processed similarly.

⁶A similar RANOVA with target type (red vs. square) added as a factor revealed the main effect of target type to be significant, $F(1, 14) = 30.79, p < 0.01$, as well as its interaction with display density, $F(1, 14) = 5.39, p < 0.05$, reflecting faster RTs for red relative to square targets, 569 versus 600 ms, as well as stronger density effects for red than for square targets, -35 versus -11 ms. The target type \times target sequence interaction was marginally significant, $F(1, 14) = 4.30, p = 0.06$, due to somewhat stronger DREs for red relative to square targets, 18 versus 11 ms. Critically, the target type \times display density \times target sequence interaction was far from significance, $F < 1, p = 0.54$, indicating that the absence of density \times target sequence interaction was not specific for red targets.

⁷Additionally, the dense displays in these studies, unlike the present study, did not control for local density variations; that is, in some trials with dense displays, the target could be presented completely surrounded by distractors while in others it could appear with only few distractors nearby, rendering the display conditions effectively sparse.

⁸Note that the available evidence would not appear to necessitate this assumption. For example, Müller et al. (2004) showed that having to encode (and, occasionally, report) the location of a singleton target does not automatically enforce encoding of other (response-irrelevant) target properties: They found that while location discrimination performance was near perfect reportability of selection-relevant target properties was at chance levels.

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